AUTOMATIC SELECTION OF THE OPTIMUM SPINDLE SPEED IN HIGH-SPEED MILLING

By

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Abstract of Dissertation Presented to the Graduate School
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AUTOMATIC SELECTION OF THE OPTIMUM SPINDLE SPEED IN HIGH-SPEED MILLING

By

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In order to take full advantage of recent developments in tool materials, a method is proposed to overcome the limitations placed on the milling operation by flexibilities in the machine-tool-workpiece system. Using a new type of stability diagram developed through time-domain simulation, it is shown that by adjusting the spindle speed so that the frequency with which the teeth pass the workpiece is equal to the dominant natural frequency of the system, it is usually possible to achieve substantial improvements in stability without necessitating basic changes in the NC part program.

An algorithm is presented which is capable of making this adjustment automatically and which requires only a vibration signal from the cut, the number of teeth on the cutter, and the spindle speed. No prior knowledge of the dynamic characteristics of the machine or workpiece is required, and the algorithm is even able to respond to changing dynamic charateristics (e.g. tool changes or machining across a thin web). The selection of spindle speed is made iteratively, and adjustments in feed rate are made in order to limit the magnitude of vibrations that may develop during the selection process. It is shown through simulation and experimental work that the algorithm converges to the best speed rather rapidly if convergence is possible. Cases are enumerated where convergence is not possible, and the original part program must be altered.

The portion of the operational time of a machine which is usually required for proving part programs can be greatly reduced. Substantial gains in metal removal rate are possible using this algorithm, and the hardware required for implementation is commonly available and relatively inexpensive.

CHAPTER I
INTRODUCTION

Scope of the Problem

There are many instances in mechanical manufacturing where relatively large quantities of metal must be removed by milling. For example, the mass of the aircraft component shown in Figure 1 was reduced from 2700 kg to 200 kg by milling [1]. Approximately 1 cubic meter of aluminum was converted into chips. If the machining was completed over the course of 24 hours, an average power of about 9.6 kw (13 hp) would be consumed during the machining operation. This example is indicative the enormity of the milling required for many operations in the aerospace industry, where the desire for large, integral, yet lightweight structures is common.

In such milling operations, large chatter vibrations are often accepted as a fact of life because of the economic necessity of high metal removal rates. Subsequent to the milling, considerable effort must be exerted in hand finishing chatter marks, since the marks act as stress concentrations and reduce the fatigue life of the part. It

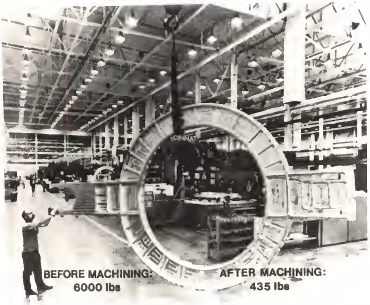


Figure 1 Machining a Large Aerospace Component

Source: Aggarwal,T. Raj, "General Theory and Its Application in the High-Speed Milling of Aluminum," Handbook of High Speed Machining Technology, R. I. King, ed., Chapman and Hall, New York, 1985.

has been estimated [2] that approximately 25% of the mechanical manufacturing cost of modern production aircraft is represented by end milling operations. An additional 20 to 30% of that is represented by hand finishing the unacceptable surfaces produced during machining. Clearly, considerable savings could be realized if the machining time could be reduced, and the resulting surface finish improved.

It should be noted here that the machining time quoted is the actual chip-making time, not the time required to produce the part. Auxiliary operations such as loading and unloading the part and changing the tool make the total operation time considerably longer. The chip-making time is quoted however because the results of this work allow this time to be shortened, but do not affect the time required for the other operations.

As an additional example, one could consider the manufacture of automobile body stamping dies at a large automobile company, such as General Motors. These dies are machined from large cast iron blocks, and a skin of approximately 12 mm must be removed over the entire surface surface of the two die halves, an area of about 15 square meters. For each die, then, a total of about 0.25 cubic meters of cast iron must be removed in the skinning process alone. Assuming the machining consisted only of the skinning operation, and that it would be completed in 24 hours, an average power of 4 kw (a little over 5 hp) would be required. In practice, on average only about half that power can be used because chatter develops at higher metal removal rates. Again, the time quoted is the actual chip-making time and also does not include any milling to machine the frame, but rather just the die surface.

For each car model, some 30 dies are required at each of 4 plants, and considering 8 models per year, a total of almost 1000 dies is required per year. Reducing the machining time without a substantial increase in other costs would be a decided advantage. The machines that do the milling usually have substantially more power available than can be used. For example, the spindle motors on the new die-machining cells specified by GM can provide 150 kw, but because of the rather flexible attachments required to reach into die cavities, they must usually operate at powers more than an order of magnitude lower in order to avoid the onset of chatter.

Development of Milling Capability

Throughout the development of modern machining capability, as tool materials have been improved, increasingly heavy demands have been placed on the machine tools themselves. As tool materials capable of withstanding higher cutting speeds and higher feed rates were developed, a demand was created for stiffer and more powerful machines which could utilize the tools to their fullest potential.

Recently, advances in tool materials have allowed the cutting speeds and feeds in some operations to be increased by an order of magnitude. Particularly, the introduction of silicon nitride inserts for the machining of cast iron makes it possible to use surface cutting speeds of almost 1600 m/min [3]. These inserts are also capable of withstanding relatively high feed rates (some cutting tests have even shown that very low feed rates may lead to an increase in tool wear for these materials). Coated carbides and whisker reinforced ceramics have made improved cutting speeds and feeds possible for aluminum and steels as well. As a result, developments have reached a stage where there are tool materials capable of withstanding very high metal removal rates, and machine tools exist which are capable of supplying the power required for such cuts. The barrier remaining which prevents immediate substantial improvement in metal removal rates comes from chatter vibrations.

Limitations on Metal Removal

The remaining factor preventing full utilization of milling capacity is the insufficient structural stiffness of the various components of the machine-tool-workpiece combination. Spindles which are capable of achieving the high speeds required for high metal removal rates are almost never stiff enough. As a result of insufficient stiffness, unacceptably large vibrations may develop between the tool and workpiece which spoil the workpiece, damage the cutter, or even damage the spindle. Because of this limitation, many large machine tools are constrained to operate at powers far below the potential of the other system elements (drives, tools, etc.). In order to overcome this limitation, considerable research effort should be devoted toward the goals of improving the design of high-speed spindles with regard to stiffness, and given a particular spindle, to selecting cutting parameters so as to achieve the maximum possible metal removal rate. The focus of this research is on the latter item.

It will be shown that a primary reason for the unacceptably large vibrations in milling is a phenomenon called "regeneration of waviness," which can result in self-excited vibrations (also referred to as unstable vibrations or chatter). However, as spindle speeds have increased to a point where the frequency of tooth impacts can approach the dominant natural frequency of the system (usually 400 - 800 Hz for these high-speed, high-power machining centers), it has become possible to select spindle speeds such that the stability of the system against chatter is very high. This will all be discussed in detail in Chapter III.

Additionally, it was always supposed that a second probable cause of vibration would be the resonant forced vibration, if the tooth frequency were near a natural frequency of the system (precisely where the self-excited vibrations are least likely to occur). In Chapter IV, further research will be presented which shows that forced vibrations are not as formidable a problem as previously believed.

Potential for Improvement

Because spindle speeds and powers have increased, the possibility of using the effects of the stability lobes [4] to substantially increase the metal removal rate has become more attractive, and selection of cutting conditions which take advantage of the lobes has become an important consideration. For some time analytical techniques have been available which permit the stability of a machining operation to be predicted based on the measured dynamics of the particular machine-tool-workpiece combination. As a result, alternate cutting conditions (lower axial or radial depth of cut, or different spindle speed) could be recommended where the metal-removal rate could be improved without sacrificing the quality of the finished part. The beneficial effects of the stability lobes were repeatedly demonstrated [5,6], but there existed as yet no clear criteria for determining the "optimum" conditions. Even so, improvements of 100 to 300 % in metal removal rates were common, and the term "magic speed" was frequently used to describe the phenomenon [4,5,6].

There were difficulties with practical implementation of the research because the techniques which were developed to find the magic speed [5,6] were very dependent on the particular configuration of the machine and required the use of highly trained personnel and rather expensive equipment for proper measurement of the system dynamics. Any changes which significantly altered the dynamic characteristics of the system (tool changes, extension or retraction of a ram, change in workpiece mass, milling across a thin web, etc.) required new measurements and new computations of the stability limits. Both the measurements and computations were rather time-consuming and had to be performed off-line.

In order to use the previous developments efficiently to obtain the full advantage of the stability lobe effects, it is necessary to overcome the practical implementation difficulties described above. Specifically, a control technique is needed which can automatically adjust the milling parameters to keep the cut stable if the dynamics should change, or even if the dynamics are unknown. The requirement for expensive equipment and highly-trained personnel should be eliminated in order to make the system practical for wide-spread use.

CHAPTER II
REVIEW OF THE LITERATURE

While the very basics of the theory of regenerative machine tool chatter have been understood for more than 30 years, and there exist many case histories of substantial improvements in the stability of particular operation based on this understanding, comparatively little research has been conducted into adaptive control schemes for on-line chatter avoidance. In this chapter, it is intended to review some of the significant work of other researchers in this field, as they relate to the current discussion.

Historically, there have been two distinct groups involved in chatter research: those who approach the problem from the point of view that the machining process is a stochastic one, and therefore best understood by statistical analysis, and those who take the deterministic viewpoint, basing new predictions on developing an understanding of the underlying processes.

Statistical Models

The former group can trace much of its roots to the work of S. M. Wu, whose paper, "Dynamic Data System--A New Modeling Approach" [7] laid the groundwork for statistical analysis of machining operations. Here he introduced the Modified Autoregressive Moving Average Vector (MARMAV) model as a basis for identifying the unknown parameters of a multivariate process. Particularly, this can be related to machining processes by considering a two-input, one-output multivariate model as shown in Figure 2. Here X_{2t} and X_{1t} represent the sampled input and output respectively, and a'_{1t} and a'_{2t} are assumed in general to be correlated white noise sequences. The joint input-output model of the system is formulated as

$$\begin{bmatrix} \phi'_{11}(B) & \phi'_{12}(B) \\ \phi'_{21}(B) & \phi'_{22}(B) \end{bmatrix} \begin{Bmatrix} X_{1t} \\ X_{2t} \end{Bmatrix} = \begin{bmatrix} \theta'_{11}(B) & \theta'_{12}(B) \\ \theta'_{21}(B) & \theta'_{22}(B) \end{bmatrix} \begin{Bmatrix} a'_{1t} \\ a'_{2t} \end{Bmatrix}$$

where B is the backshift operator $BX_t = X_{t-1}$, and the ϕs and θs are polynomials in B. This is an Autoregressive Moving Average Model. The algorithm in Wu [7] allows development of a similar model, but where a'_{1t} and a'_{2t} are uncorrelated. This allows determination of the parameters of the multivariate model based on consideration of two univariate models. Model parameters are initially guessed and then improved using a nonlinear least squares technique. The order of the model is increased repetitively until a statistically adequate model is found.

This process has been used for structural identification [8], where considerable success has been achieved. In this application, the technique is somewhat

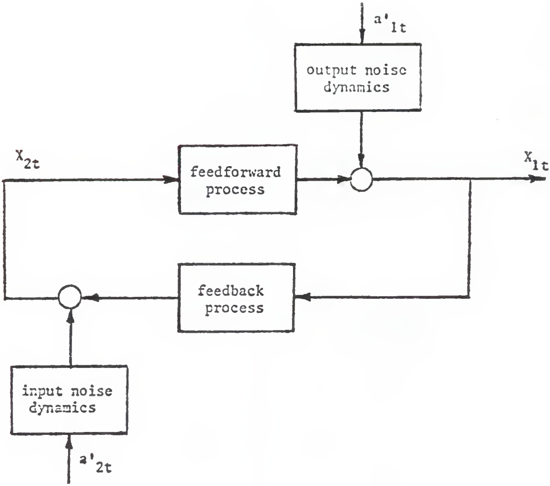


Figure 2 Two-Input, One-Output Multivariate Model

similar to analysis by random noise excitation and is fully capable of correctly identifying natural frequencies and mode shapes, and damping ratios. Unlike random noise excitation, however, because the magnitude of the input is not known, the transfer functions produced are provided without scale.

Following on this basis, at least one attempt was made at controlling machining chatter based on observation of changes in the autoregressive model. Eman has reported success observing changes in the estimated damping ratio on-line as an indication of impending chatter in a turning operation. He says, "Rather than predicting the stable regions of the cutting process before cutting, based on experiments, or developing controllers based on a priori assumed models of the cutting dynamics of the structure, a suitable chosen variable has been measured and used for on-line identification of the machining process and subsequently to predict and control its stability" [9, p.38]. However, by its very nature the control scheme requires some time to identify the changing dynamic characteristics and was effective here because the chatter developed slowly (generally on the order of 4 to 8 seconds). Also, if the system began the cutting operation in an unstable condition, the controller again required some time to gain a knowledge of the parameters of the forecast model and to begin making reasonable corrections. The corrections recommended are changes in cutting speed and feed rate, based on a theoretical time dependent relation between those parameters

and the damping ratio. The time dependency is developed by applying the identification procedure repeatedly and observing the changes in the estimated parameters. Corrections are thus made based on an observation of the previous trend, assuming the development of chatter to be a gradual phenomenon following the trend.

Deterministic Models

From the deterministic point of view, considerable effort has gone into the development of models which accurately include the various physical phenomena involved in the development of chatter. Of particular interest regarding the present discussion are the works by Tlusty and Ismail [10,11]. These papers show that the relative flexibility between the tool and workpiece (quantitatively expressed by a relative transfer function) can lead to chatter through a phenomenon called "regeneration of waviness." Each tooth involved in the cut encounters a surface left behind by the preceding teeth, and the phase relationship between the waves is the crucial factor in the development of chatter. Additional details which were required for subsequent improvements in the model (such as proper accounting for the tooth jumping out of the cut) were also outlined here.

As an outgrowth of the recognition of the key role of the phasing between the vibration of the cutter and the waves left on the surface by previous teeth, several attempts have been made at controlling chatter by varying spindle speed to disturb the regeneration of the waves. Hoshi et al. [12] describe the effects of varying spindle speed on a turret lathe, a vertical lathe, and on several boring operations. While the boring tests resulted in generally poor surface finishes, they report success in disturbing the regeneration of waviness in the turning operations subject to several important caveats.

First, on systems with comparatively high flexibility, the tendency to chatter was increased by the variable speed. Additionally, if the inertia of the spindle is large, then considerable power is required to cause changes in the spindle speed at a rate sufficient to have any effect. They caution that the large peak current encountered per every cycle of the speed fluctuation would require a comparatively larger capacity in the power amplifier and drive motor. For this reason, this is not a practical solution for chatter control in milling. Sexton and Stone [13] also have shown through simulation that in general the modest benefits to be obtained through variation of the spindle speed are not worth the expense of producing the variation.

Most of the remainder of this work is based on analysis made possible by a refined dynamic model developed by the author [5], and based on an earlier similar model developed by W. Zaton [14]. Such models account for most of the physical phenomena involved in milling operations. As will be discussed in Chapter III, the model used in this analysis has the form of a time-domain simulation, and as a result, all of the relevant parameters are easily accessible so that their role in the development of chatter can be studied.

CHAPTER III
ANALYSIS OF CUTTING DYNAMICS

In this chapter, the previously developed models of the cutting process and the analysis techniques will be briefly reviewed for those who are not already familiar with the work. Although the models are not new, and are not presented here as such, they are helpful as a basis for the new and original developments presented in subsequent chapters.

A Simplified Model

A classical method will now be briefly shown for developing relationships which lead to the concept of stability lobes. It is similar to that developed by Tlusty [15] and is based on the early work of Tobias [16] in this area. In order to linearize the model of the cutting process some simplifying assumptions are required. First, it will be assumed that the force produced on any tooth involved in the cut will be simply proportional to the area of the chip being removed. The constant of proportionality is referred to as the "cutting stiffness," or specific power, and is denoted here as K_s. A typical value of K_s for cast iron would be 1500 N/mm^2. The formula for the force on any tooth is given by

$$F = K_s \; b \; h$$

where b is the axial immersion and h is the chip thickness.

The second simplifying assumption is that all of the teeth are parallel, so that the forces produced by the teeth all have the same direction. Essentially, the assumption is that the cutter has an infinite diameter. Finally, it must be assumed that at all times, the teeth remain in the cut. That is, regardless of how large the vibrations become, the teeth are assumed to always be in contact with the workpiece. The simplified model is shown in Figure 3, which is taken from reference [5].

As previously mentioned, regeneration of waviness is the primary cause of self-excited vibrations in milling. This is illustrated in Figure 3, where it can be seen that each tooth that passes through the cut encounters the surface produced by the preceding teeth. Each tooth is therefore exposed to a variable cutting force. Depending on the phasing between the undulations left on the surface by the preceding teeth and the displacement of the current tooth, the amplitude of the vibration may increase or diminish.

As is shown in reference [5], by examining in the phase plane representation (Figure 4) of the case where the vibration amplitude during the passage of subsequent teeth neither grows nor is attenuated, the equation which relates

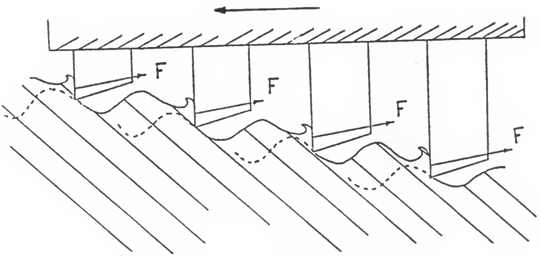


Figure 3 Simplified Model of a Milling Cutter

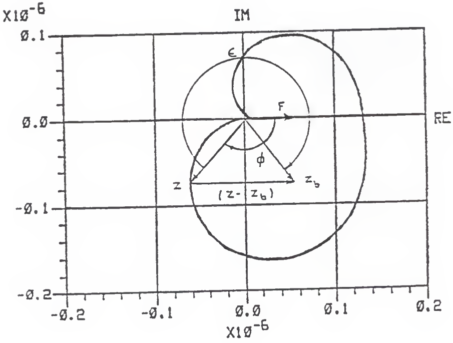


Figure 4 Phase Plane Representation of the Cutting Operation

Source: "Chatter, Forced Vibrations and Accuracy in High-Speed Milling," S. Smith, Master's Thesis, University of Florida, 1986.

the limiting axial depth of cut to the displacement transfer function of the system may be obtained, and it is given by

$$b_{lim} = \frac{-1}{2\ K_s\ \mathrm{Re}[G]} \tag{1}$$

where Re[G] denotes the real part of the oriented transfer function of the system. The oriented transfer function is the force-displacement transfer function at the end of the tool, multiplied by the geometric gain representing that transfer function's participation in the resulting vibration (see reference [5]).

The spindle speed may be related to the transfer function of the system by the expression

$$\frac{f}{n\ m} = N + \frac{\epsilon}{2\ \pi} \tag{2}$$

where f is the frequency in Hz at which chatter will develop if the system is unstable, n is the spindle speed in rpm, m in the number of teeth on the cutter, N is the number of complete integer cycles of the vibration between subsequent teeth, and ϵ is the fractional part of the cycle, or phase shift, between subsequent teeth. From the diagram in Figure 4, it may be seen that ϵ is given by

$$\epsilon = 2\ \pi - 2\ \tan^{-1}\left(\frac{\mathrm{Re}[G]}{\mathrm{Im}[G]}\right) \tag{3}$$

By choosing a frequency, evaluating the oriented transfer function of the system, and computing b_{lim} and n for the various integer values of N, the well known stability lobe diagram is produced.

Time-Domain Simulation

More accurately, a time-domain simulation may be used to develop the stability lobe diagram. Such a simulation is described in reference [5]. The time-domain model of the cutter is shown in Figure 5, and it can be seen that the dynamics are expressed as lumped-parameter, not necessarily linear, multiple-degree-of-freedom systems in each of two mutually independent coordinate directions. Basically, as the cutter is moved through the cut in small steps, the force on each tooth is computed, and the resulting displacement of the cutter is computed. Cutters with straight teeth (or helical teeth in shallow axial immersions) are assumed for simplicity here, but true helical teeth can be modeled as well. The formula for force on any tooth is given by

$$F = K_s\, b\, (z - z_0 + f_t) \tag{4}$$

where

F = cutting force

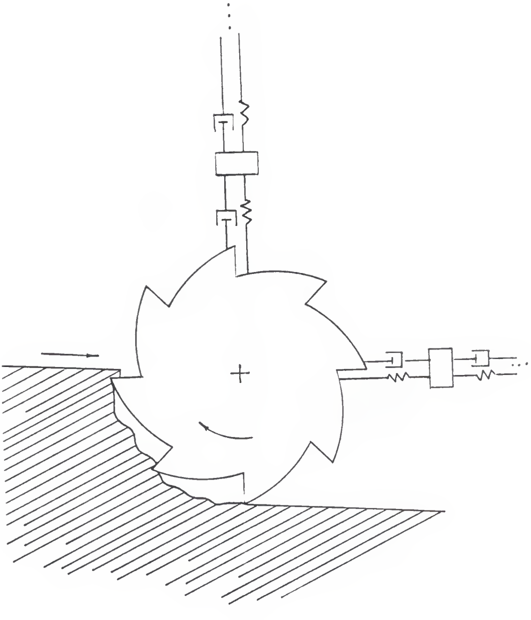


Figure 5 Time-Domain Simulation Model

K_s = specific power of workpiece material

z = current displacement of the cutter normal to the cut

z_0 = surface normal to the cut (from preceding teeth)

f_t = feed per tooth normal to the cut

Such nonlinearities as the cutter jumping out of the cut, and the changing orientation of the force vector can be included in all detail. The simulation stability lobes are generated by repeatedly running the simulation at various speeds and axial depths of cut, and observing whether or not chatter develops.

Stability Lobes

We now compare the computed and simulated stability lobes for an experimental spindle based on tapered roller bearings, and equipped with a 102.6 mm (4 inch) diameter shell mill with 8 teeth on a 152.4 mm (6 inch) long extension tool holder. The schematic diagram for this spindle is shown in Figure 6. From experimental measurements of the transfer function, modal parameters which describe the system were obtained, and they are given in Table 1. The computed (upper) and simulated (lower) stability lobes for the system described in Table 1 are shown in Figure 7. The lobes in the upper section have been marked as they

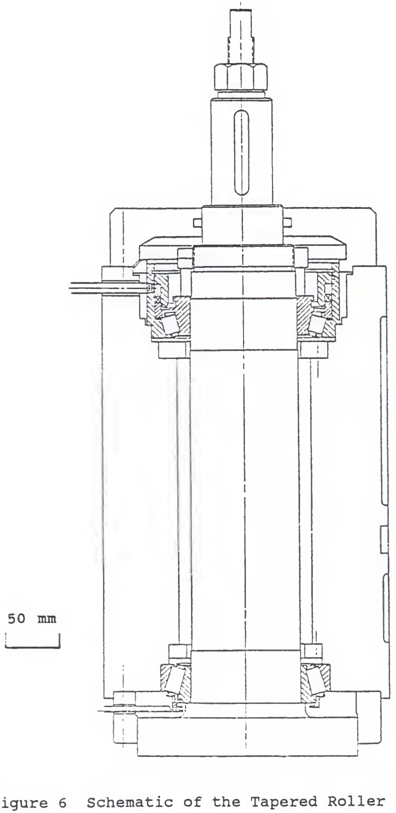


Figure 6 Schematic of the Tapered Roller Bearing Spindle

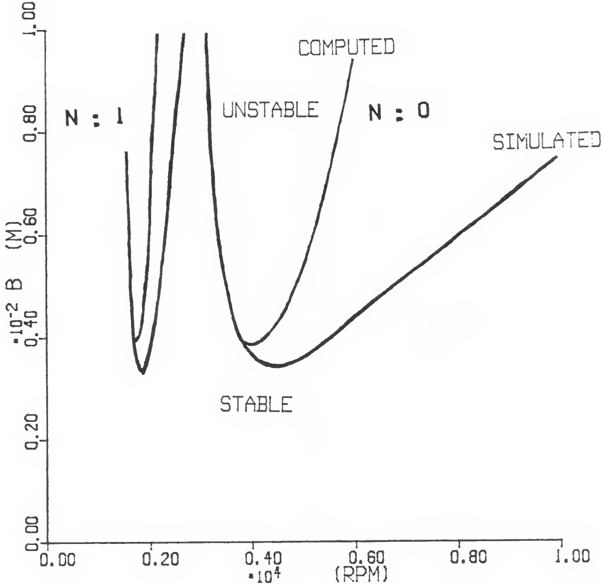


Figure 7 Computed and Simulated Lobes

correspond to various values of N in Equation (2). The diagram is for a radial immersion of 1/2 (a_r = 1/2 the diameter of the cutter), and the lines indicate the boundary between stable and unstable cuts.

The largest stable peak on the graph is at the spindle speed where the tooth frequency would equal the dominant natural frequency of the system, and increasingly smaller peaks are found at smaller integer fractions of that speed. It may be seen that the simplified model locates the most stable peak accurately, but shows the lobes to be much narrower than the simulation. As a result, the stabilizing effect as the spindle speed is increased above the last lobe is not as dramatic as the simplified model would indicate. It may someday be possible to obtain a substantial stabilizing effect by achieving spindle speeds far above the last lobe; however, a speed significantly higher than those currently available would usually be required. The time-domain simulation has been repeatedly shown to have very good agreement with actual cutting test data [5,6] and is used extensively in predictions of performance of spindles based on their measured or computed dynamic models.

Table 1. Example system parameters

Direction	Mode	Frequency (Hz)	Stiffness (N/m)	D. ratio
X	1	260	2.26E8	0.1
	2	389	5.54E7	0.04
Y	1	150	2.13E8	0.1
	2	348	2.14E7	0.1

CHAPTER IV
OPTIMUM CUTTING PARAMETERS

Parameters Available for Manipulation

In order to develop an algorithm capable of automatically selecting optimally stable cutting conditions, it is first necessary to decide which of the parameters affecting the stability of the cut are available for manipulation. A basic vision of the function of the algorithm is required.

In the course of this work, the optimization routine is envisioned as a sort of "patch" for part programs written without regard to system dynamics. That is, if a programmer writes a part program which through ignorance or error causes chatter to develop, then the optimization routine systematically adjusts the available parameters so that a stable, acceptable cut is achieved, if that is possible.

Currently, without knowing about the dynamics of a system or the basics of chatter theory, a programmer may easily specify cuts which, though well within the power and torque limits of a given machine, will produce chatter. Such an error is only discovered when the program is tried on the particular machine. If an error exists, the programmer must then redistribute the cuts and try again until all of the programmed cuts are within acceptable limits. A recent study [17] has shown that approximately 25% of the time a machine is in operation is spent in proving part programs. In the future, it may be possible to include the system dynamics and simulation or simulation results in the CAD software so that as the part program is being developed, the programmer will know if the cuts he is specifying will be acceptable or if they should be redistributed.

As a patch, the desired function of the algorithm is to avoid chatter by manipulating those parameters which would not require alteration of the basic part program. Obviously, changing the axial or radial immersion in general requires more passes to be included and risks interference with other previously machined structures or surfaces. Changing the number of teeth on the cutter during a cut would require a tool change, and is also clearly not desirable. In milling, only the spindle speed and the feed rate may in general be altered without altering the geometry of the part, or necessitating basic changes in the part program. Additionally access to these parameters is usually available even if the information about the system controller is incomplete (for example in the form of feed rate or spindle speed overrides).

Stability Lobes

Once the parameters appropriate for alteration have been selected, the objective of the optimization routine must be selected. It is possible that the optimization strategy will be different depending on the desired result. There are many possible objectives, but one of the most important is to keep the amplitude of the variable component of the cutting force below a specified limit. This force is frequently responsible for damage to the tools or workpiece (especially in machining steels or titanium alloys), and provides the periodic excitation that drives any forced vibrations of the system. An example of a case where this objective is important would be a heavy roughing cut in cast iron, where the main goal is to have the metal removal rate as high as possible without damaging the tool or workpiece. The resulting surface finish would not be a major concern, if a finishing pass would follow.

Another possible target is to keep the amplitude of the variable component of the displacement as low as possible. It will be shown later that this variable component can result in error in location of the finished surface (even though the surface finish may be excellent). The amplitude of the displacement is also responsible for the volume of the sound produced during the cut (although any vibrating body contributes to the overall sound level, it is the displacement of the end of the tool that is of concern in the following analysis).

In some instances, the surface finish may be the deciding factor, and the objective would be to keep the surface roughness to a minimum. Such cases would include machining parts where fatigue life is an important consideration, and finishing passes on most parts. Certainly there are other possible objectives such as maximizing tool life, but they will not be considered here.

The stability lobes as obtained using the classical simplifications or even simulation (Chapter III) denote only the boundary between stable and unstable cuts. They do not contain any specific information with respect to the possible objectives, and therefore cannot be used to locate optimum conditions. In order to overcome the limitations of the traditional stability diagram, several new charts have been developed as shown in Figure 8. All of the results presented in Figure 8 are based on the same system described in Chapter III (the dominant natural frequency is 389 Hz).

Figure 8a shows lines of constant peak-to-peak (PTP) force as obtained by time-domain simulation for a slotting cut in the same direction as the X parameters in Table 1. The horizontal axis is spindle speed, and the vertical axis is axial depth of cut, and the figure bears some resemblance to Figure 7. It may be clearly seen that at the speed where tooth frequency equals the natural frequency (there are 8

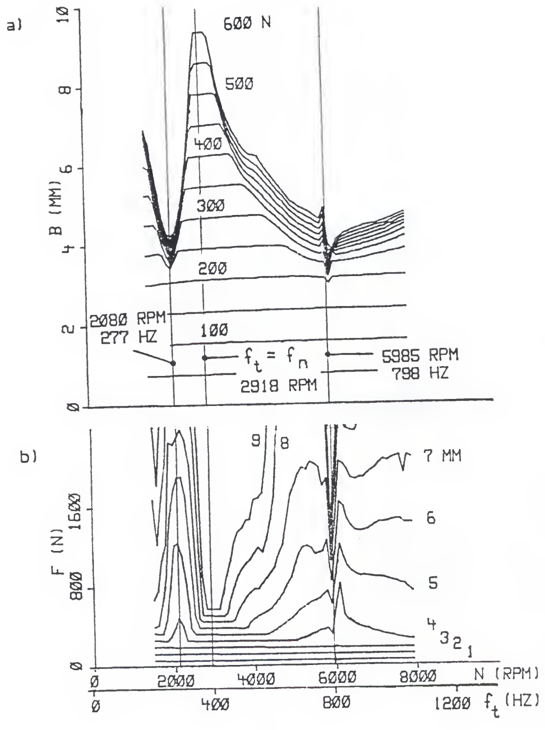


Figure 8 New Stability Charts

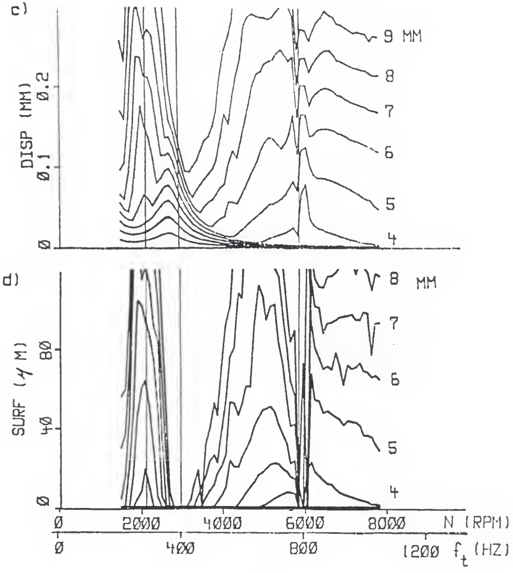


Figure 8 Continued

teeth on the cutter in this case), rather large axial depths of cut still result in low PTP force levels. The limit of stability as previously determined can be seen to correspond to a rather dramatic increase in the PTP force.

In Figure 8b, the same information is shown in a different way. Lines of constant axial depth of cut are plotted on axes of spindle speed and PTP force. It may be seen here that for a given axial depth of cut, the minimum PTP force is obtained at and near the speed where tooth frequency equals natural frequency. Figures 8c and 8d are similar diagrams, but displaying lines of constant PTP displacement and lines of constant PTP surface finish, respectively.

Optimum Spindle Speed

It becomes obvious from examination of Figure 8 that it would be desirable to choose spindle speeds such that the tooth frequency is equal to the dominant natural frequency of the system for each of the three objectives mentioned above. A method will be shown in Chapter V which facilitates the selection of this optimum speed for many systems of practical interest.

Actually, in the force and surface finish portions of the diagram it is seen that any speed within the stable region is about as good as any other, and all that is really required is to reach the stable area. Because the speed where tooth frequency equals natural frequency will be shown to be the easiest to find, and it is anyway the speed farthest from the unstable region and therefore less likely to slip into chatter if the speed should change slightly, this will be the target speed. In the displacement section, it can be seen that the true minimum PTP displacement is not exactly at the speed where tooth frequency equals natural frequency, but it is close, and the above recommended speed is far superior to any unstable speed.

The somewhat surprising results that within the stable region, the PTP force is practically a constant for a given axial depth of cut regardless of the speed, and that in the same region, the PTP surface finish is almost zero deserve a little explanation. Figure 9 shows the displacement of a particular tooth as it passes through the cut as well as the surface profile left by the preceding teeth in a stable cut. It should be noted that the figure shows the "unrolled" cut, so that the vertical scale indicates the displacement or surface normal to the cut at all times. The cut is 1/2 immersion up-milling, and the surfaces and displacements for the passage of two consecutive teeth are shown. It may be seen that the vibration of the cutter is in phase with the

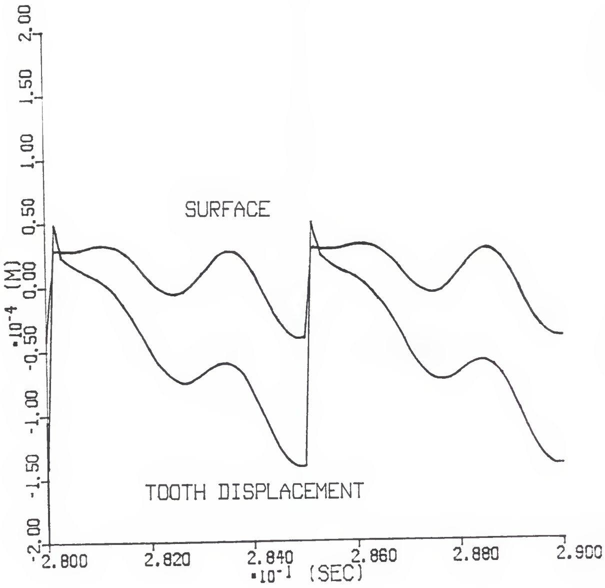


Figure 9 Tooth Displacement and Surface

undulation left on the surface by the previous teeth. If the axial depth of cut is fixed, the cutting force seen by that tooth is proportional to the chip thickness, that is, proportional to the difference between the two lines shown. Figure 10 shows that difference. Again, this is the difference normal to the cut, and it may be seen that although vibration exists, the difference between the position of the tooth and the surface produces a chip whose thickness is the same as if no vibration existed (in this case the feed per tooth is 0.1 mm). From Figures 9 and 10, it may be seen that the regeneration of waviness which causes so much difficulty with chatter actually disturbs the development of the resonant forced vibration.

Additionally,it can be seen that the surface left behind is being generated at the instant the tooth enters the cut only. Only at this time is the deflection of the cutter imprinted on the finished surface. At other instants, the deflection is imprinted on metal that is subsequently removed. When the cut is stable, the displacement of the cutter is exactly in phase with the passage of the teeth, and the resulting surface finish is very good, although it may have an error in location depending on the magnitude of the cutting force.

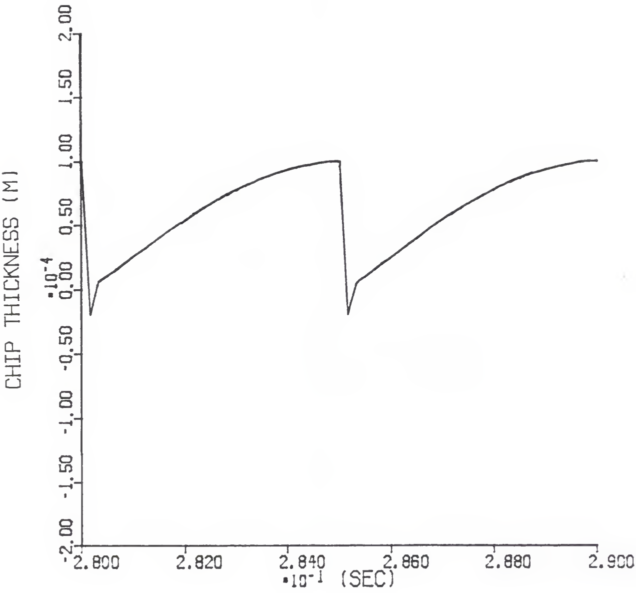


Figure 10 Resulting Chip Thickness

For radial immersions other than 1/2, similar conclusions about the optimum speed apply. In Figure 11 is the force level diagram for the same system involved in a slotting cut. In this case, notice that within the stable region, the PTP force levels are very small, even at relatively large depths of cut. This is in agreement with the theoretical result [5] that the cutting force does not contain a variable component in a stable slotting cut where the cutter has an even number of teeth greater than two. Of course in reality in a stable slotting cut, some variable component arises from the cutter run-out which can never be completely eliminated. Figure 12 shows the force level diagram for a 1/4 immersion cut, and Figure 13 shows the diagram for a 1/8 immersion cut. These diagrams confirm the previous result [6] that at the basic limit of stability, the product of radial and axial immersion is practically a constant in systems where the dynamics in two mutually perpendicular directions in the plane of the cut do not differ substantially. In all the force level diagrams, it may be clearly seen that if chatter is a problem, and axial depth of cut is constrained, then if a stable speed exists, it will be found at the speed where the tooth frequency is equal to the dominant natural frequency.

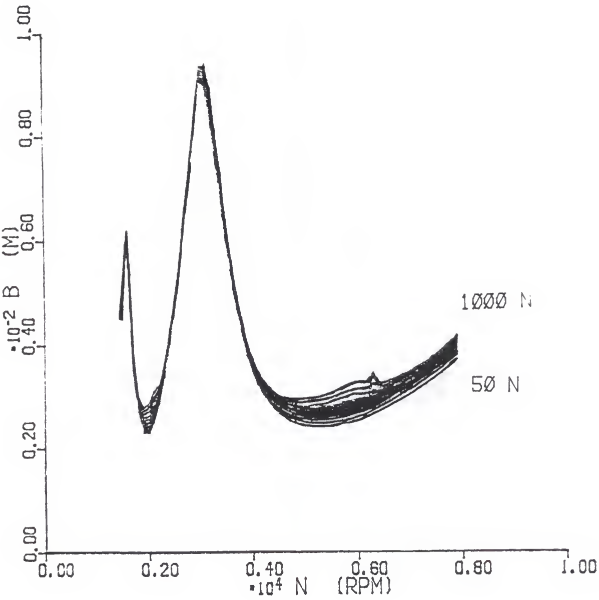


Figure 11 Slotting Force Level Diagram

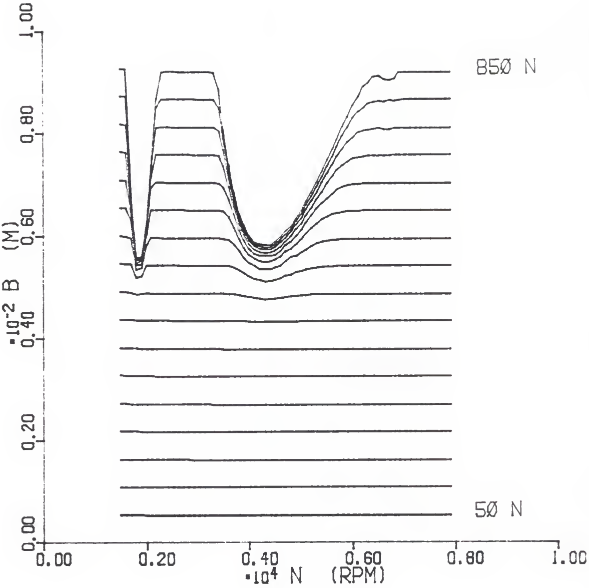


Figure 12 1/4 Immersion Force Level Diagram

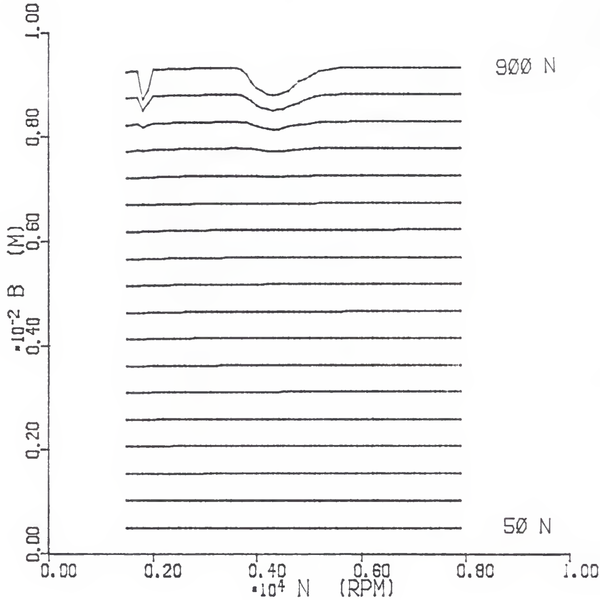


Figure 13 1/8 Immersion Force Level Diagram

Optimum Feed Rate

It has been shown through simulation and cutting tests that the feed rate does not substantially affect the stability of a particular machining operation [6]. The feed rate does however affect the magnitude of the vibrations which develop (higher feeds of course produce larger vibrations). Therefore, in situations where chatter is likely to be encountered, it is most desirable to keep the feed rate as low as possible to avoid damage to the tool. This is particularly true in the machining of steels and titanium alloys where the relatively high specific powers lead to large forces which can easily break the tools. At normal feed rates, chatter in machining these materials is dangerous and should be avoided.

On the other hand, once stable conditions have been achieved, it is more advantageous to use as high a chip load as possible. This will not lead to instability (provided that the spindle speed is not significantly changed by the increased power required to make the cut) and maximizes the metal removal rate. The maximum permissible feed is typically dictated by the strength of the inserts, but may on other occasions be dictated by available machine power, maximum slide velocity, or very stringent force or vibration constraints.

CHAPTER V
DISCUSSION OF THE ALGORITHM

There are several possible strategies for moving to the most stable speed (or at least reaching a speed within the stable region). The displacement transfer function of the system could be measured using standard modal analysis techniques and the dominant natural frequency selected based on analysis of that transfer function. This method is the one currently employed for improving the stability of some machining operations; however, this is an off-line technique and is situation specific. That is, it depends very strongly on the configuration of the machine (extension of the ram, mass of the workpiece, length of the tool, etc.) at the time the transfer function is measured. It is likely that one or more of these parameters will change significantly during the course of a milling operation, and in that case the previously determined stable speed is no longer valid. Measurements are thus required for each new tool and in a wide variety of machine configurations, which is a rather formidable task.

It might be possible to take a test cut with each tool for which the cutting force is approximately known, and using this as an input, measure the response of the system and compute the transfer function. Again, this is rather cumbersome and is valid only for the particular conditions under which the test cut is performed. There is a more practical method, however, which takes advantage of the fact that for a particular spindle speed, as the axial depth of cut is increased and the cut becomes unstable, there is a pronounced change in the spectrum of the cutting force.

Stability Lobes and the Chatter Frequency

Taking again the example system of →P.35 Table 1, we now look at the spectrum of the cutting force obtained by time-domain simulation in various operational conditions. Figure 14 shows the spectrum corresponding to 6000 rpm and axial depth of cut b = 1 mm. The only apparent peaks are the tooth frequency, and a second harmonic of the tooth frequency. This cut is stable. Figure 15 shows the spectrum for a cut at the same speed, but with b = 5 mm. Here, the tooth frequency and its harmonic are still clearly visible, but now a peak corresponding to the chatter frequency has appeared. This cut is just at the limit of stability. In Figure 16 the cut is only slightly deeper at b = 6 mm, and the peak indicating chatter is clearly dominant. This is an unstable cut. Notice that this cut crossed the limit of stability on the highest (N = 0) lobe, and that the chatter frequency which developed was lower than the tooth

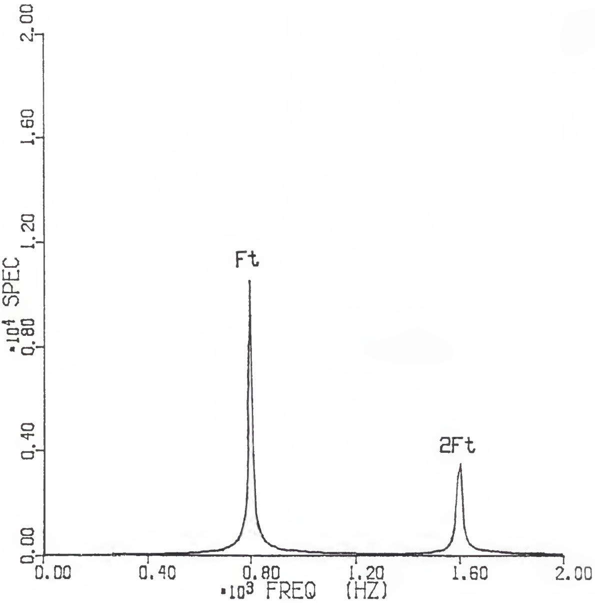


Figure 14 Simulated Force Spectrum, n=6000 rpm, b=1 mm

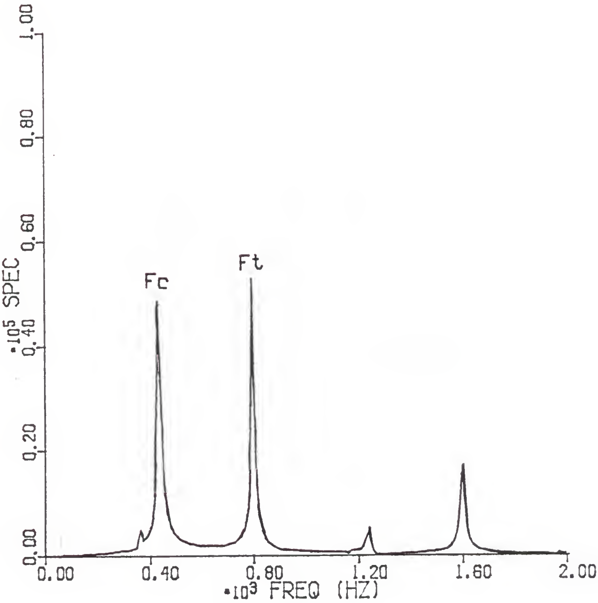


Figure 15 Simulated Force Spectrum, n=6000 rpm, b=5 mm

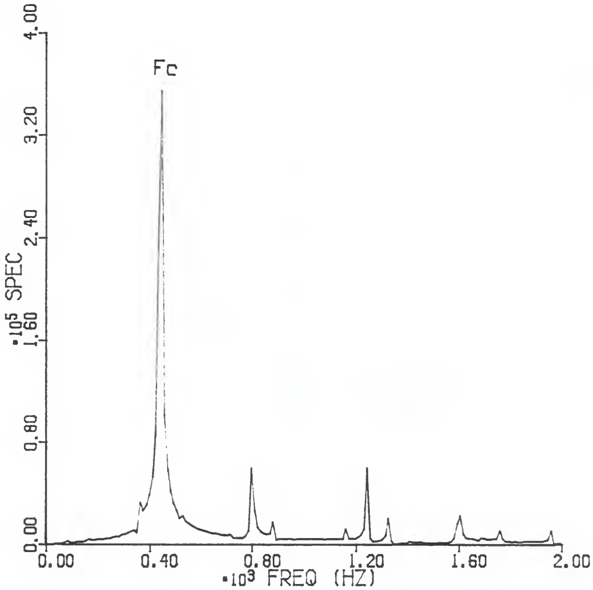


Figure 16 Simulated Force Spectrum, n=6000 rpm, b=6 mm

frequency. As will be shown, this is always the case. Figure 17 shows a cut even more severely unstable at b = 10 mm, and clearly the chatter frequency did not change with an increase in the axial depth of cut.

Let us choose another spindle speed which could involve the N = 1 lobe. Figure 18 shows the spectrum for a cut with n = 2000 rpm and b = 2 mm. Again, this is a stable cut and the only visible peaks correspond to the tooth frequency and its harmonics. In Figure 19, the axial depth of cut has been increased to 4 mm, and the chatter frequency is by far the dominant peak. In this case, however, the chatter frequency is higher than the tooth frequency. Again, it will be shown that this is always the case. In Figure 20 is shown the spectrum for the same cut, but with an axial immersion of 6 mm, and again the chatter frequency is seen not to change with an increase in the axial depth of cut.

For the case where the tooth frequency is equal to the natural frequency, at about n = 3000 rpm, the frequency of the dominant peak corresponds to the tooth frequency even for very deep axial immersions. This is illustrated in Figure 21 (n = 3000 rpm, b = 1 mm), and Figure 22 (n = 3000 rpm, b = 10 mm). It will now be shown, using the simplified model that produced the upper lobes in Figure ~~5~~7, that any chatter that develops in the last lobe occurs at a frequency less than the tooth frequency, and that any chatter that

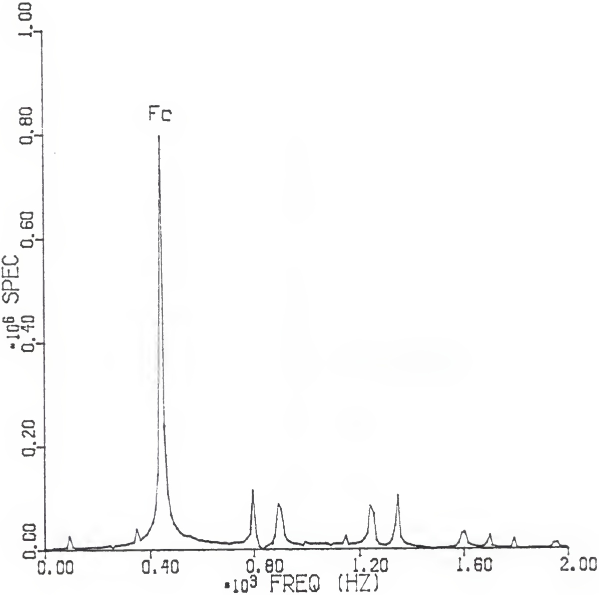


Figure 17 Simulated Force Spectrum, n=6000 rpm, b=10 mm

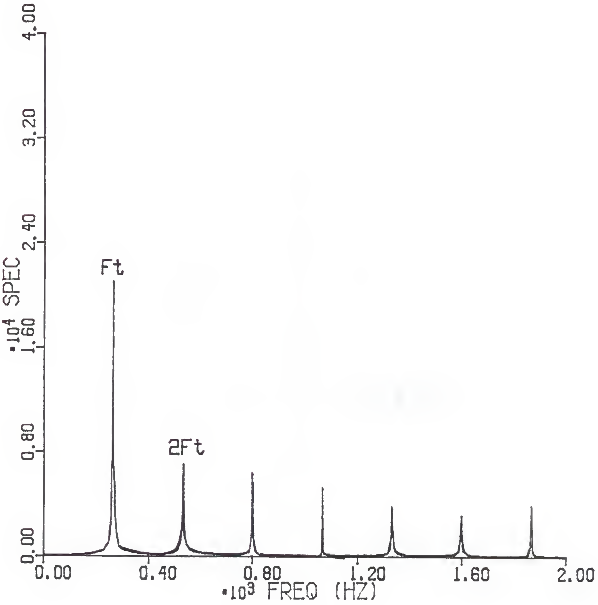


Figure 18 Simulated Force Spectrum, n=2000 rpm, b=2 mm

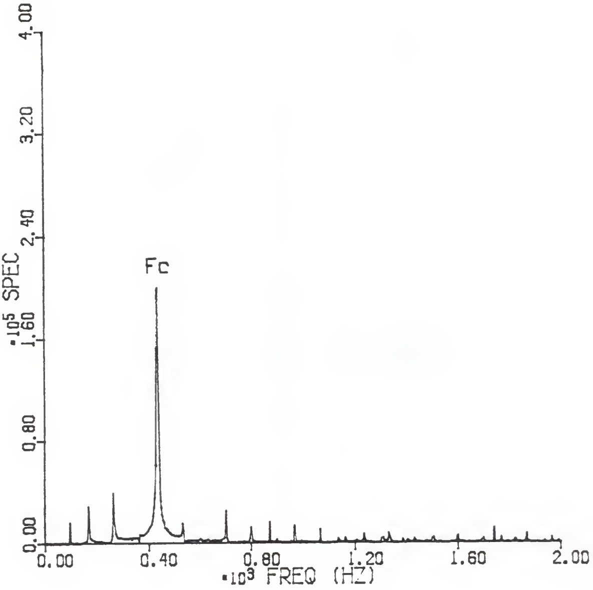


Figure 19 Simulated Force Spectrum, n=2000 rpm, b=4 mm

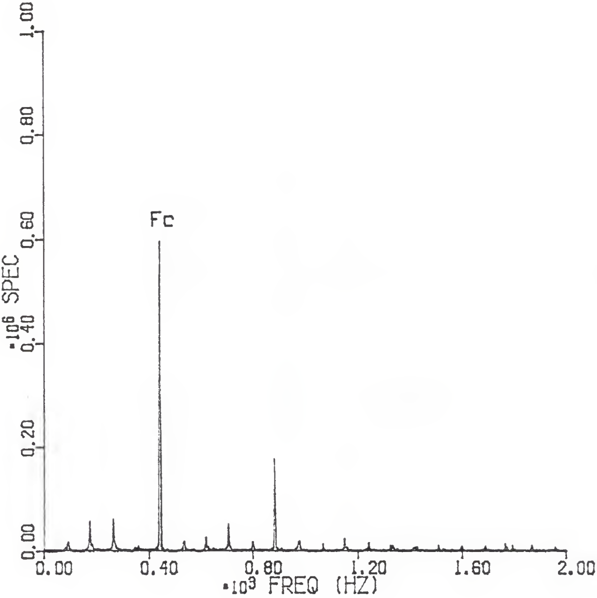


Figure 20 Simulated Force Spectrum, n=2000 rpm, b=6 mm

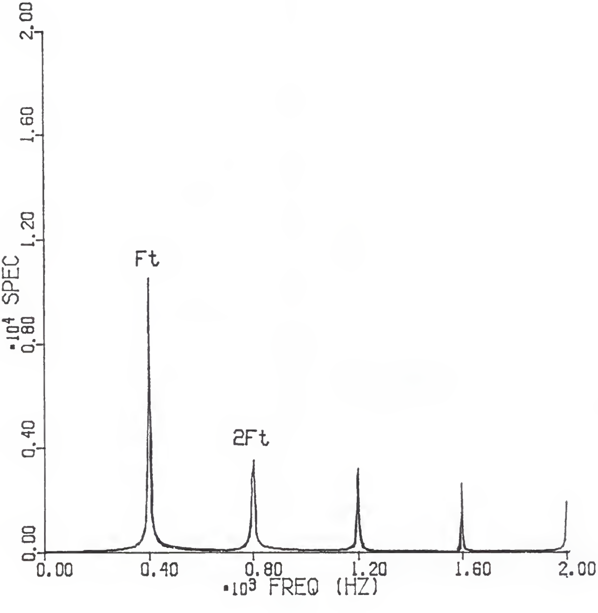


Figure 21 Simulated Force Spectrum, n=3000 rpm, b=1 mm

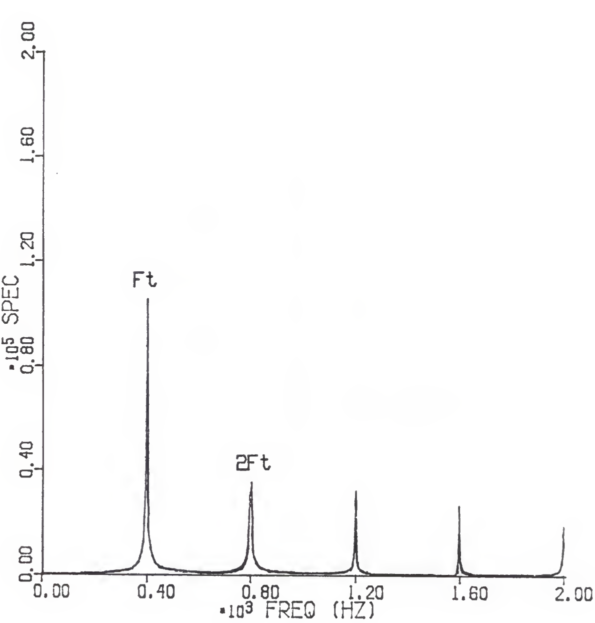


Figure 22 Simulated Force Spectrum, n=3000 rpm, b=10 mm

develops in any lower lobe occurs at a frequency higher than the tooth frequency.

As shown in Figure 23, each point on the stability lobe for a given value of N corresponds to a single point on the real part of the transfer function of the system as expressed in Equations (1), (2) and (3). If the limit of stability is crossed, then the phasing is such that the self-excited vibrations develop with the frequency of the corresponding point on the transfer function. According to Equation (2), if $N = 0$, then the ratio of chatter frequency to tooth frequency is less than 1. For a lobe corresponding to any other value of N, this ratio is greater than 1. This is shown diagrammatically in Figure 24, which shows the frequency of chatter that would develop vs. spindle speed for the same system as in Figure 8. The line which corresponds to tooth frequency equals natural frequency is included, and it passes between the $N = 0$ lobe and all others.

Outline of the Optimization Procedure

The strategy which now seems attractive is to check the spectrum of the cutting force during a cut. If the peak corresponds to the tooth frequency within some small tolerance, then the system is stable. Otherwise, the system is chattering and the spindle speed should be adjusted so

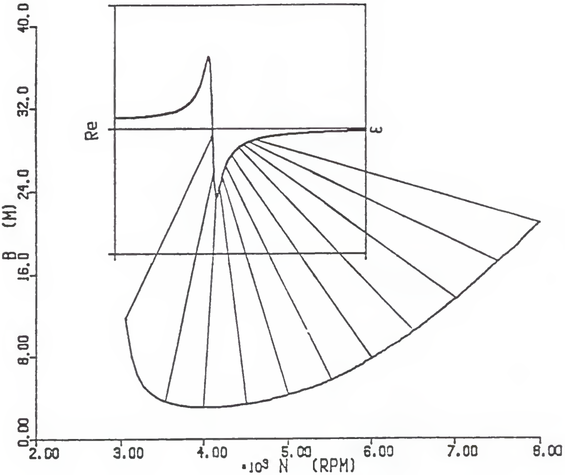


Figure 23 Transfer Function and Stability Lobes

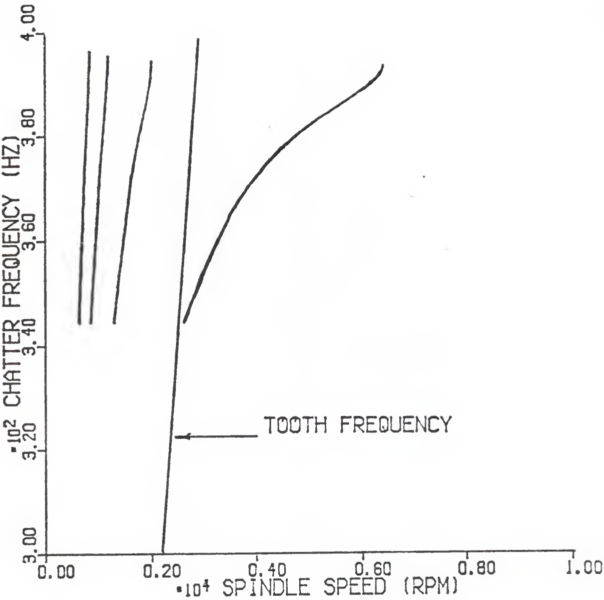


Figure 24 Spindle Speed vs. Chatter Frequency

that the new tooth frequency will be equal to that seen in the spectrum. Regardless of the initial cutting condition, this moves the spindle speed toward the stable peak. This could be understood from the analytical development of the lobing diagram as attempting to minimize the phase angle ϵ in Equation (2).

Simulation has shown that this strategy converges to the optimum speed within only a few iterations, but in the convergence process, some cuts are specified which are quite unstable, and the PTP force may become very large before the optimum is reached. For example, if the initial cut parameters in Figure 8 were b = 8 mm and n = 8000 rpm, the cut would be just above the limit of stability. In converging to the optimum spindle speed (about n = 3000 rpm), several iterations are required, and cuts in the worst area for self-excited vibration (around n = 5000 rpm) will be specified.

In order to avoid this difficulty, the other parameter available for manipulation, feed rate, may be used. Reducing the feed rate does not change the stability of the system, but it does reduce the amplitude of the established vibration. This is because at the lower feed rates, the cutter begins to jump out of the cut at much smaller amplitudes, and in this way limits the developing vibration at a lower level. The essential information required to adjust the spindle speed (dominant frequency of the cutting force) is, however, not affected by the feed reduction.

The proposed strategy is basically outlined in Figure 25 as it would be implemented in machining of steel, titanium, or even cast iron. That is, it is indicated for those cases where the development of chatter at normal feed rates is dangerous, and must be avoided if possible. Required inputs to the system are the maximum and minimum permissible chip load (feed per tooth), number of teeth on the cutter, the maximum spindle speed, and the maximum permissible amplitude of the objective. In this work, no attempt is made to quantify what the maximum permissible amplitude of the objective parameter should be. This is a matter that must be decided depending on the requirements of the end user. The maximum and minimum permissible feed rates are dictated as described in Chapter IV, and the maximum spindle speed is dependent on the particular spindle.

Initially as the cut begins, a series of short cuts will be taken until the correct spindle speed is found so that any chatter caused by the originally specified cut will be kept to a minimum. Therefore, as the cut starts, the chip load is set to the minimum permissible chip load.

The section marked loop L1 now comes into action, and is the loop which adjusts the spindle speed. In this section, input is required from the vibration transducer, whatever that may be, and from an encoder attached to the

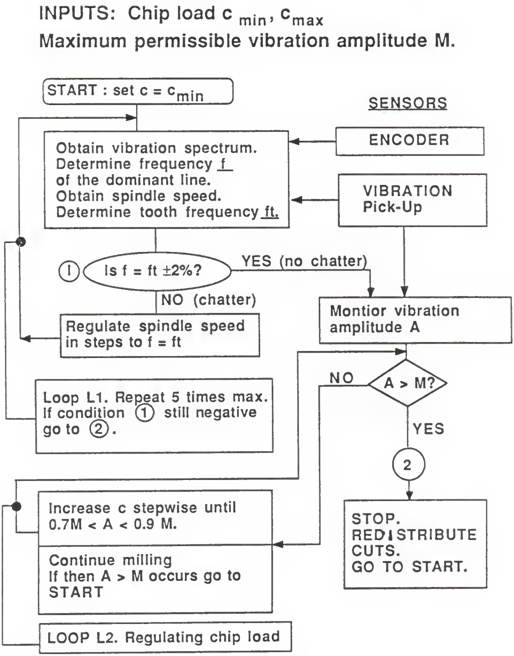

INPUTS: Chip load c_{min}, c_{max}
Maximum permissible vibration amplitude M.
START : set $c = c_{min}$
SENSORS
ENCODER
Obtain vibration spectrum. Determine frequency f of the dominant line. Obtain spindle speed. Determine tooth frequency ft.
VIBRATION Pick-Up
① Is f = ft ±2%?
YES (no chatter)
NO (chatter)
Regulate spindle speed in steps to f = ft
Montior vibration amplitude A
Loop L1. Repeat 5 times max. If condition ① still negative go to ②.
NO
A > M?
YES
2
Increase c stepwise until 0.7M < A < 0.9 M.
Continue milling If then A > M occurs go to START
STOP. REDISTRIBUTE CUTS. GO TO START.
LOOP L2. Regulating chip load

Figure 25 Flow Chart for Optimization Algorithm

spindle. The signal from the vibration pick-up is processed through a Fourier Transform (an FFT can be hardwired to save processing time), and software is used to locate the frequency of the dominant spectral line. In software, the signal from the encoder, which indicates spindle speed, is converted into the tooth frequency. If the two frequencies are equal within a small tolerance to account for resolution difficulties in the FFT and in the computed tooth frequency, then the system is stable, and no further changes are made in the spindle speed. If the two frequencies are not equal, then the spindle speed is regulated so that the new tooth frequency will be equal to the previously determined dominant spectral line. This regulation can be provided as either a spindle speed override, or directly as a change to the NC program block, depending on the level of access available.

In order to keep any damage from chatter to a minimum, the cuts which are made are only as long as necessary to acquire a sufficient number of samples for the FFT (experience has shown that the self-excited vibrations develop almost immediately as the cut begins). That is, after the samples have been collected and while the computations are being performed, a "FEED HOLD" can be issued so that no milling will take place during the computation, and while the spindle speed is being adjusted to the new speed. When the supervisory system is ready, a

"CYCLE START" command is issued, and the next small cut is taken.

It will be discussed in the next chapter that there are some instances in which it is not possible for the algorithm to converge to a stable spindle speed, and for this reason the number of iterations of the L1 loop must be limited. If this limit is reached, then it is unlikely that a stable speed will be found, and the machine is stopped, with an appropriate error message.

If a stable speed is found, processing in the algorithm proceeds into the section marked loop L2, where the feed rate is adjusted. As shown in Chapter IV it is desirable to use as large a chip load as possible without exceeding the specified limits. It was seen in the Figure 8a, and repeatedly in simulation and experimental work that in a stable cut the PTP vibration amplitude increases in linear proportion to an increase in the chip load. In this loop, the chip load is increased in steps until either the maximum chip load is reached or the objective parameter is exceeded. In this loop, the signal from the vibration transducer is sampled, and its amplitude computed in software. The measured amplitude is compared to the specified limit, and the chip load is increased in small steps. When the measured amplitude is close to, but still below the specified amplitude, then the milling is allowed to proceed. As with the spindle speed, adjustments to the feed rate are made as either feed rate overrides or as changes to the NC block.

Again, it will be discussed in the next chapter that some situations exist where even though a stable spindle speed has been selected and the minimum feed rate is being used, the specified objective parameter may still be exceeded. The machine is again stopped in such a situation, and an appropriate error message is issued.

As the milling now continues, the only part of the algorithm required as a monitor of the cutting operation is the section which evaluates the amplitude of the vibration signal and compares it to the specified value. The section is only a small portion of the algorithm, and it has a comparatively short cycle time. If some condition now changes (the milling cutter encounters a thin web, for example) so that the amplitude exceeds the allowable limit, the milling is stopped ("FEED HOLD"), and control is returned to loop L1, as if the cut was beginning anew.

All of this is based on trying to reach the stable peak between the highest two lobes. In practical cases, this is usually the best that can be achieved, since the limit of stability rises so slowly above the last lobe that those speeds can rarely be achieved. If the optimum speed should be higher than the highest speed that the given spindle can achieve, then it may be possible to obtain some benefit between the lower lobes by choosing a spindle speed so that the tooth frequency is an integer fraction of the dominant natural frequency. However, as the integer number of waves between teeth increases, the stable peaks become smaller and smaller, and it becomes more and more likely that a stable speed cannot be found.

Alternative Implementations

In various applications, some change in the above described algorithm may seem more attractive. For example, if the machining operation is end milling of aluminum, it may not be necessary to avoid chatter absolutely. As mentioned in Chapter I, there are many instances where chatter is already permitted, and with very flexible end mills, at reasonable metal removal rates, there may exist no stable spindle speed. Of course, the forces produced by chatter in aluminum are not as severe or dangerous as in steel or titanium, and an additional safety margin against damage is provided by the flexibility of the cutter.

In such instances, it is more desirable to begin the algorithm already in loop L2, without selecting the minimum feed rate, and without attempting to determine if the cut is stable or not. If the measured amplitude is acceptable, then the milling can continue whether the cut is stable or not. If the amplitude is unacceptable, then control would be passed back to loop L1 as before during the monitoring section of the algorithm.

In other cases more than 5 iterations may be required to reach a stable speed, or the tolerance with which the two frequencies in the condition marked 1 in Figure 25 are compared may be altered. Such changes would depend on the desired result which must be specified by the user.

CHAPTER VI
SIMULATION RESULTS

Convergent Examples

Figure 26 shows the PTP force as an example simulation converges. Figure 27 shows the feed rate manipulations, and Figure 28 shows the spindle speed manipulations. The initial conditions for this example were n = 6000 rpm, b = 8 mm, and feed per tooth = 0.1 mm, and as shown in Figure 8a, these conditions would lead to a very unstable cut. The objective was chosen as PTP force level, since this is typically easiest to measure,and as an acceptable PTP force level, 500 N was selected, and a minimum feed rate of 0.1 mm was chosen. As shown in Figure 27, in the first iteration step the feed rate drops to the minimum, and from Figure 26 it can be seen that the PTP force level drops to well within acceptable limits. The feed is now held at this low level while the optimum speed is selected (Figure 28). By the third step, the optimum speed is located, and the feed is increased as much as possible without exceeding the force level specified. It can be seen that even if the initial cut parameters result in a cut that is very bad, it is possible to automatically select cutting conditions which are much more favorable in only a few iterations and to keep the PTP force levels acceptable at all times.

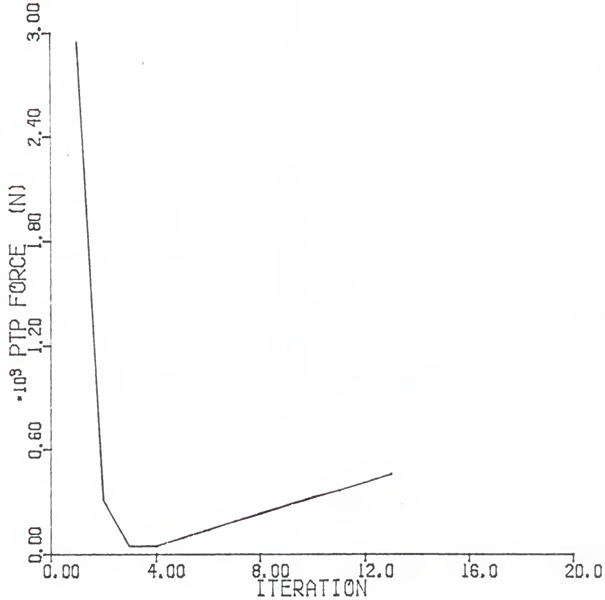


Figure 26 Converging PTP Force

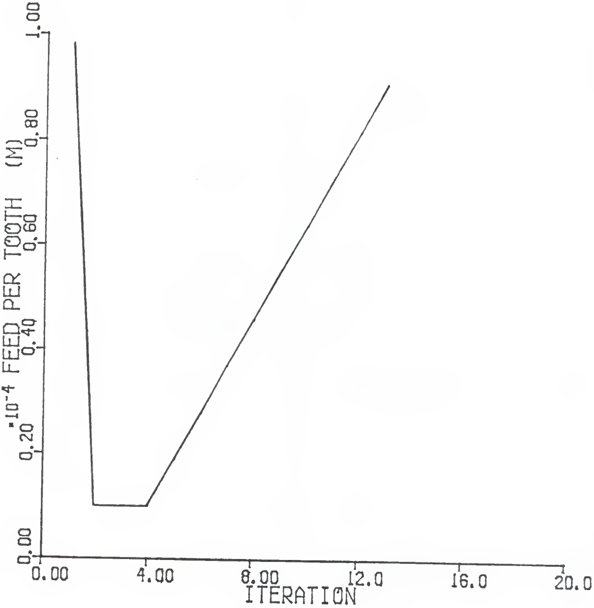


Figure 27 Converging Feed per Tooth

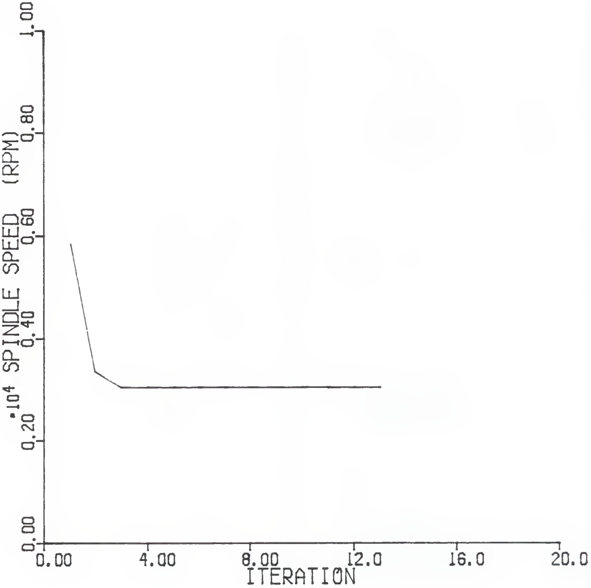


Figure 28 Converging Spindle Speed

As another example, the system described in Table 2 will be used. These parameters were obtained from measured transfer functions from a spindle based on angular contact ball bearings (Figure 29), and with a 152.4 mm (6 inch) tool extension and 101.6 mm (4 inch) diameter cutter installed. In this case, the minimum permissible feed rate was selected as 0.1 mm, and the maximum feed rate was taken as 0.2 mm per tooth. The maximum permissible spindle speed was chosen as 5000 rpm, and the permissible force amplitude was selected as 300 N. The initial conditions were axial depth of cut 1mm and spindle speed 1000 rpm. Convergence is shown in Figures 30, 31, and 32, where again it is seen that substantial improvements are made in only a few iterations.

Table 2. Example system parameters

Direction	Mode	Frequency (Hz)	Stiffness (N/m)	D. ratio
X	1	335	2.67E6	0.09
Y	1	362	3.84E6	0.04

To demonstrate the applicability to systems with more limited speed range, the above example is repeated with the constraint that the commanded spindle speed must not exceed 2300 rpm. As shown in Figures 33, 34, and 35, the algorithm eventually converges to the next lower stable peak. Although this convergence was successful, as the maximum permissible spindle speed becomes a smaller and smaller fraction of the speed where the tooth frequency equals the natural

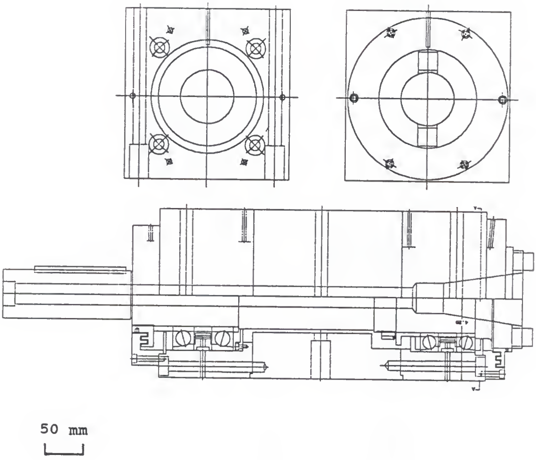


Figure 29 Angular Contact Ball Bearing Spindle

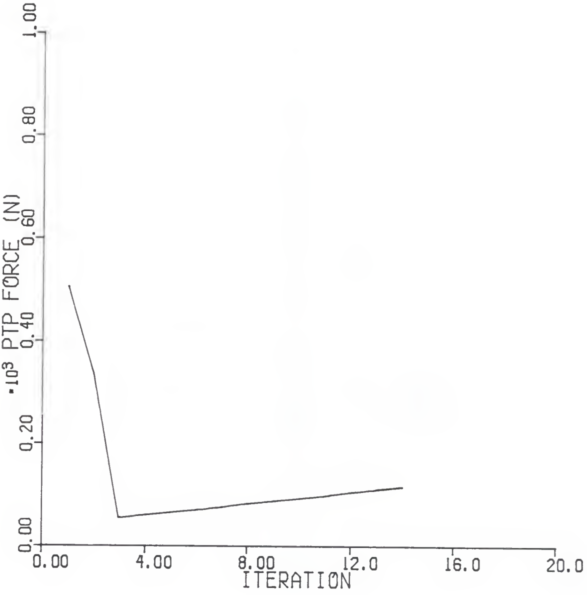


Figure 30 Converging PTP Force

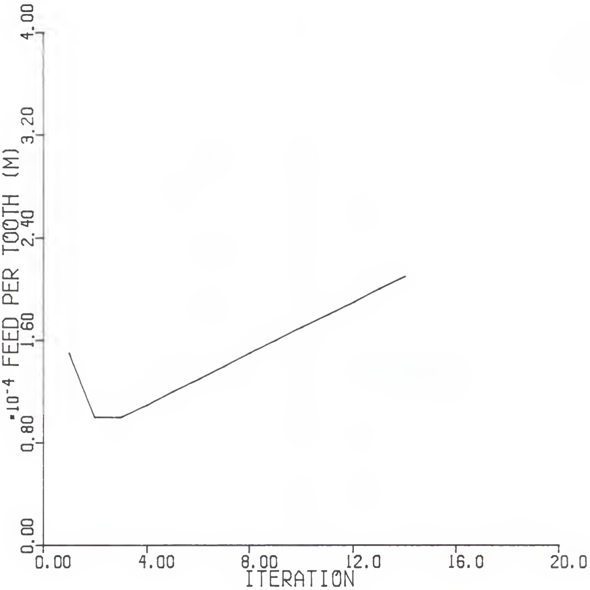


Figure 31 Converging Feed per Tooth

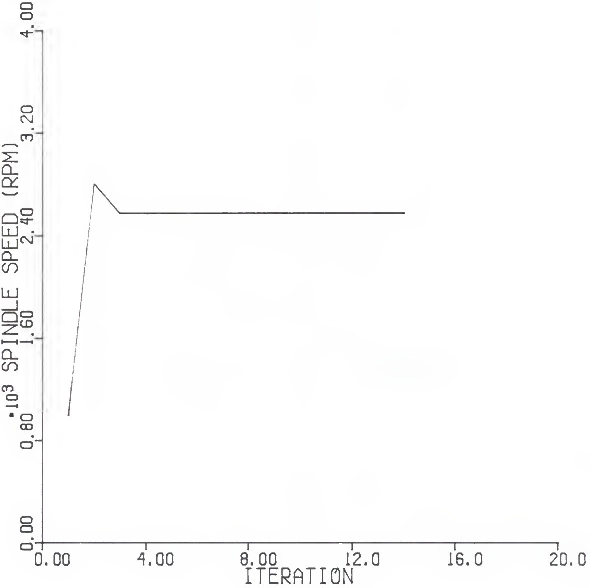


Figure 32 Converging Spindle Speed

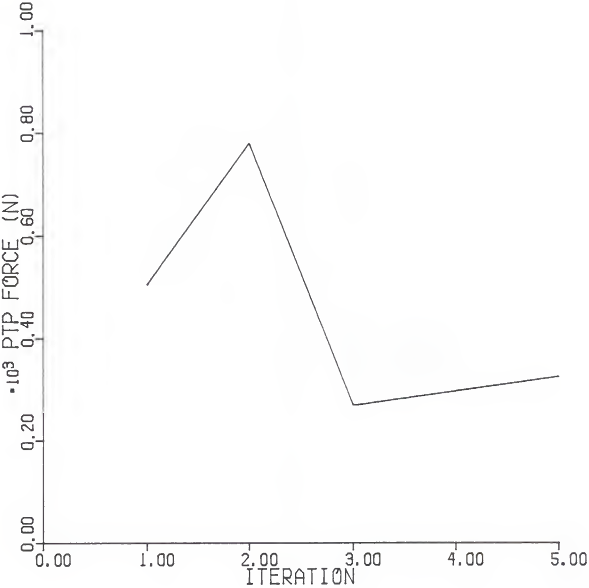


Figure 33 Converging PTP Force, Limited Spindle Speed

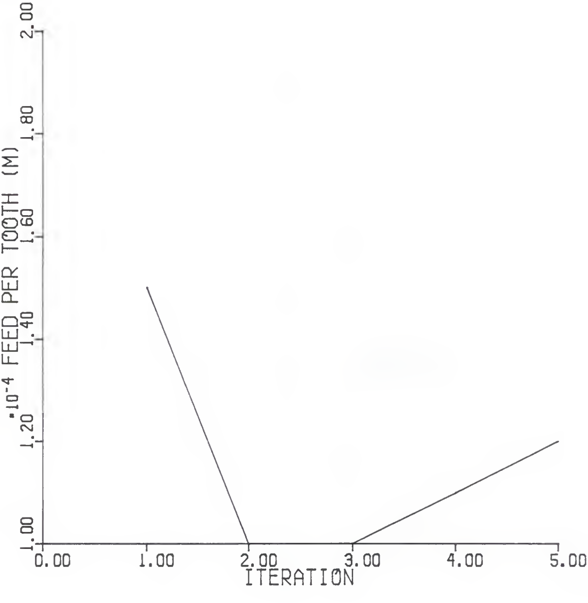


Figure 34 Converging Feed per Tooth, Limited Spindle Speed

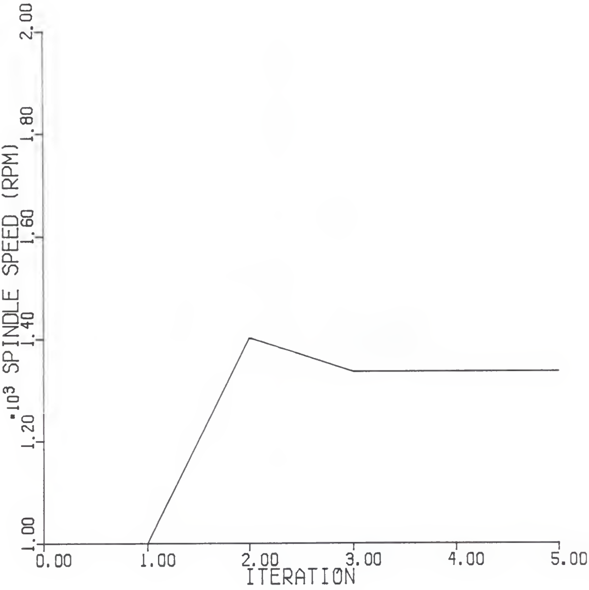


Figure 35 Converging Spindle Speed, Limited Spindle Speed

frequency, there is less and less likelihood that a stable peak can be found.

Non-Convergent Examples

In spite of the many demonstrated cases of successful convergence to stable spindle speeds, it becomes important to consider if there are any cases where the algorithm fails to successfully find a spindle speed and feed rate which satisfy the input criteria. Indeed, such cases exist in several forms.

First, there is the case where the specified cut is so horribly unstable that even when utilizing the effects of the stability lobes, it is not possible to select a stable spindle speed. Such an example is illustrated by chosing the axial depth of cut for the same system as in Figures 30-32 to be 2 mm rather than 1 mm. The failed attempt to converge to a stable speed follows along the path illustrated in Figures 36, 37, and 38 although the algorithm moves closer to the optimum speed, it repeatedly selects new speeds, but without any substantial or predictable increase in stability.

Another similar problem is illustrated in Figure 39. In this case instability can result from self-excited vibration in two different modes, and two sets of stability lobes are included in the diagram. By chance, the two modes with

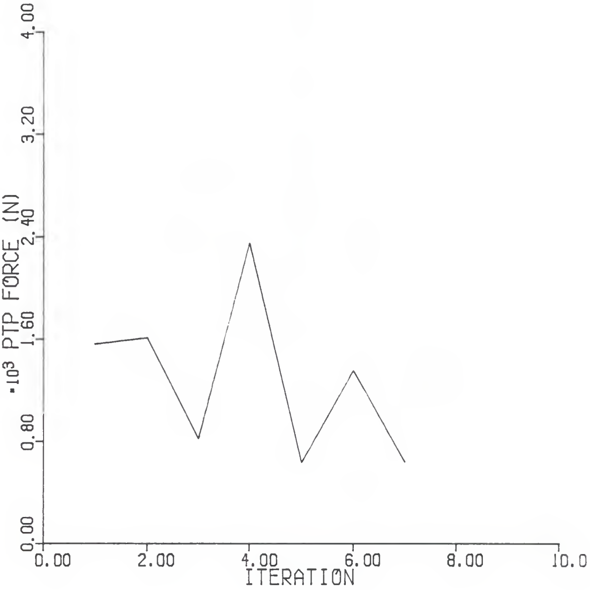


Figure 36 Non-Converging PTP Force

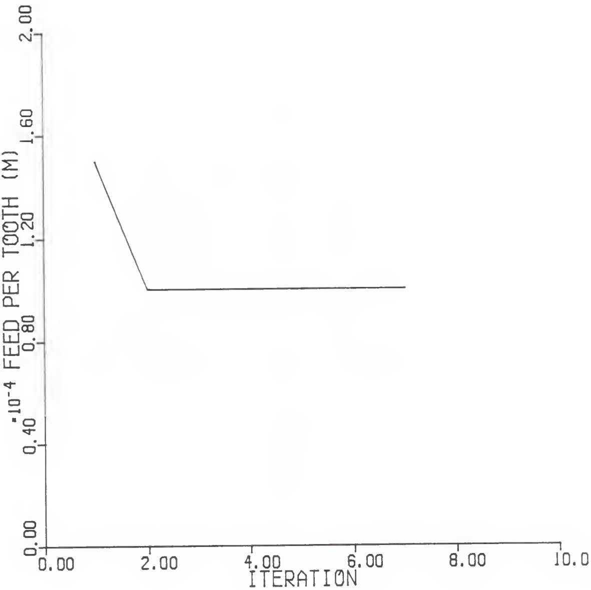


Figure 37 Non-Converging Feed per Tooth

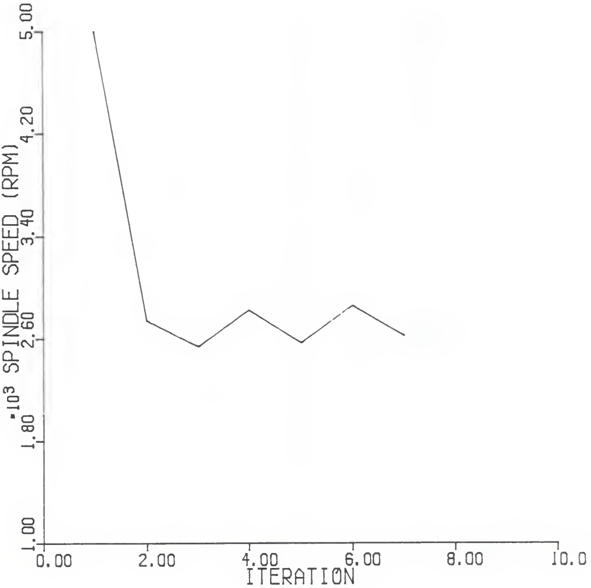


Figure 38 Non-Converging Spindle Speed

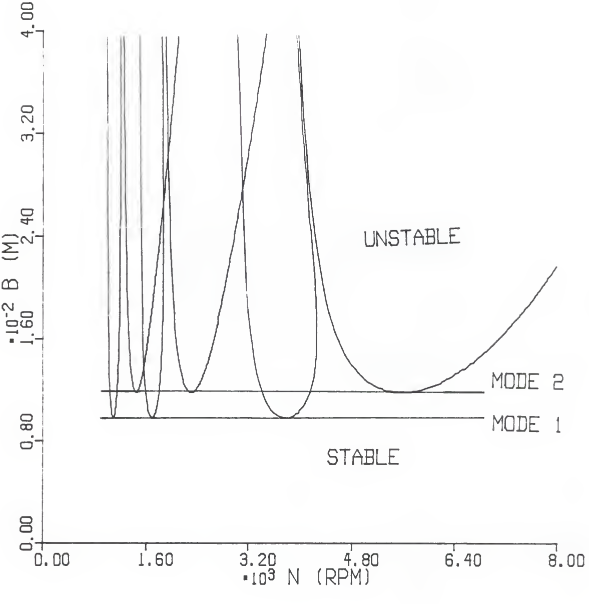


Figure 39 Interfering Lobes Resulting From Two Modes

similar dynamic stiffnesses are situated so that the lobes resulting from one mode appear in the stable regions for the other mode, and vice-versa. As the algorithm tries to converge to a stable speed, chatter in one mode guides the system to a speed which will produce chatter in the other, and the program vacillates between the two areas. This behavior is similar to the case where the system is closer to a single-degree-of-freedom, but the specified cut is too deep. It should be noted, however that in most cases convergence to a stable speed is rapid even if the chatter occurs in several modes, and that the just illustrated example is an unusual case.

For either of the above cases, the solution in the program is to stop the attempts at convergence if a stable speed has not been found within a certain number of iterations. Experience with the simulation has shown that convergence usually occurs either very rapidly or not at all and that a reasonable cut-off is six iterations. In this case, the cutting operation is stopped with a message that either the cuts must be redistributed or a more detailed off-line analysis is necessary to locate any possible stable speed.

The other type of failure occurs when the specified objective is too stringent, so that even when the most stable speed is found and the minimum feed rate is used, the resulting cut is still outside of the acceptable limits. In such a case it is simply not possible to achieve the specified cut without altering the part program, so again the machine is stopped, and an appropriate error message is displayed.

CHAPTER VII
IMPLEMENTATION CONSIDERATIONS

Transducer Evaluations

In theory and simulation, the algorithm discussed in the preceding section works very well subject to the condition that there is an adequate signal available which represents the cutting force reasonably well. In reality, it is difficult to obtain a signal indicative of the cutting force at the end of a tool in milling, since such sensors must be placed at a location somewhat removed from the actual cutting. In the following section, several of the various types of transducers available will be discussed along with their relative merits.

Table-type Dynamometer

A table-type dynamometer of the design shown in Figure 40 has been in use in the Machine Tool Laboratory at the University of Florida since 1985. It consists of two rigid steel plates separated by three matched Kistler three-directional piezoelectric load cells. As the crystals are deformed, charges in the pico-Coulomb range are produced, which are then amplified into a voltage indicative of the

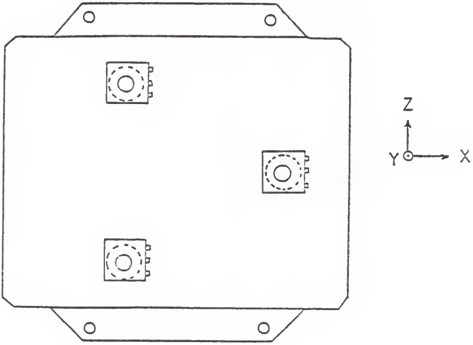


Figure 40 Table-Type Dynamometer

force the crystal is experiencing. As shown in Figure 41, the dynamometer is mounted between the workpiece and the machine table during cutting. It can be seen that the dynamometer consumes a considerable portion of the useful workspace.

In addition to the cost, difficulties arise in the practical implementation of the dynamometer mainly because the piezoelectric crystals act as springs on which the top plate of the dynamometer and the workpiece are supported. The dynamometer thus has natural frequencies and mode shapes of its own, and the cutting force signal is filtered through its transfer function. Even though the crystals are very stiff (about 4.5×10^9 N/m for the Kistler 9062 load cells), the mass of the top plate of the dynamometer combined with the workpiece can be sufficient to cause the natural frequency of the dynamometer to fall within the range of interest. Figure 42 shows an example transfer function for the dynamometer with a cast iron workpiece attached, and it is obvious that the dynamometer signal will be far from an ideal representation of the actual cutting force.

Theoretically, the signal can be improved through accelerometric compensation. That is, accelerometers can be strategically located so that their signals are indicative of the resonances of the dynamometer. The accelerometer signals can then be multiplied by appropriate constants and subtracted from the dynamometer signal to more clearly

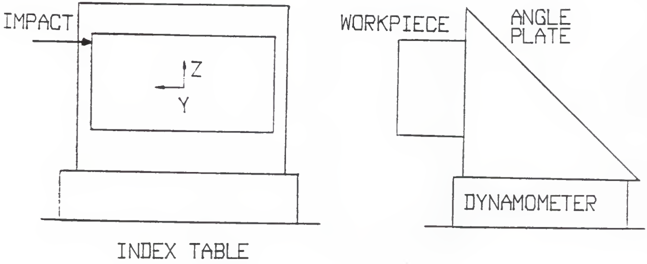


Figure 41 Workpiece-Angle Plate-Dynamometer Assembly

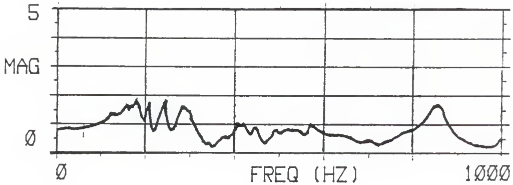


Figure 42 Dynamometer Transfer Function

indicate the cutting force [18]. However, even this scheme faces practical difficulties because the transfer function between the cutting force and dynamometer signal changes as the point of application of the cutting force varies and changes as the mass of the workpiece is reduced during the cutting operation.

Despite these difficulties, experimental experience has shown that the dynamometer signal is generally sufficient to differentiate between stable machining and chatter. However, quantitative assessments of the cutting force must be made with the dynamometer dynamics still in mind.

Accelerometer on Headstock or Workpiece

Mounting an accelerometer on the headstock or on the workpiece is relatively easy, but again these locations are somewhat remote from the cutting force. With the accelerometer mounted on the workpiece, the signal is filtered through the transfer function of the workpiece, which may change as the point of application of the cutting force varies. If the accelerometer is mounted on the headstock, then the cutting force signal is subjected to the transfer function of the spindle and housing.

Acoustic Transducers

One could consider sensing the cutting force with a microphone placed in the vicinity of the cutting operation, since the differences in various cuts are readily distinguished by an experienced operator. Pattern recognition techniques have been used with some degree of success [19] to indicate the condition of the cutting operation, but fall far short of the cutting force signal required for the implementation of the automatic speed selection algorithm (or tool breakage sensing algorithms [20]). The acoustic signal is of course produced by displacement, but the displacement of any vibrating body near the work zone is a source of noise which contaminates the signal generated by the cutter displacement.

Displacement Transducers

Of course, a displacement transducer such as a capacitance probe cannot be used directly at the end of the tool, but as shown in Figure 43 such a transducer can be used to measure the relative displacement between the spindle itself and the spindle housing. One might assume that since the displacement of the spindle is involved in the regeneration of waviness, this feedback might cause the transfer function between the force and displacement as measured experimentally (open loop) to be different from the transfer function during machining (closed loop). The following analysis will show that this is not the case.

Referring to a simplified model [15] like that used to derive the limit of stability in closed form, it has been

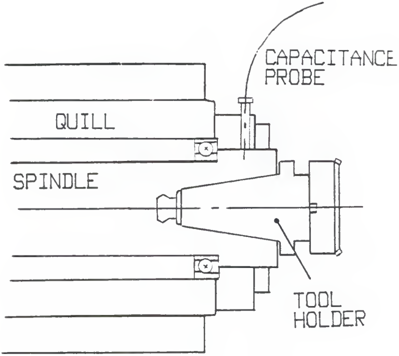
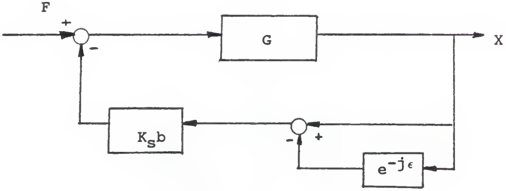
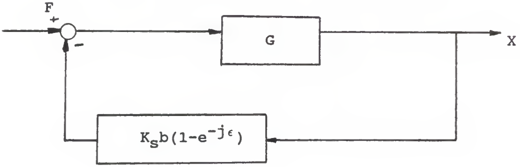


Figure 43 Capacitance Probe Mounting

shown that the block diagram of the cutting operation can be given by



This may in turn be simplified to



The closed loop transfer function is given by

$$\frac{X}{F} = \frac{G}{1 + K_s bG(1-e^{-j\epsilon})}$$

where ϵ is the relative phase shift between the current displacement of the cutter and the surface left behind by the previous tooth. It has been shown that ϵ is given by

$$\epsilon = 2\pi - 2\tan^{-1}\left(\frac{\mathrm{Re}[G]}{\mathrm{Im}[G]}\right)$$

where G is the direct transfer function of the spindle system evaluated at the end of the spindle.

If we assume that the spindle system can be represented by a single-degree-of-freedom system composed of a mass m, spring k, and damper c, then ϵ is given by

$$\epsilon = 2\pi - \tan^{-1}\left(\frac{m\omega^2 - k}{c\omega}\right)$$

The closed-loop transfer function can then be written as

$$\frac{X}{F} = \frac{1}{-m\omega^2 + k + c\omega j + K_s b - K_s b e^{-j\left[2\pi - 2\tan^{-1}\left(\frac{m\omega^2 - k}{c\omega}\right)\right]}}$$

Numerically evaluating this transfer function over a wide frequency range shows that the open-loop transfer function is identical with the closed-loop transfer function provided that the system is stable, see Figures 44 and 45. If the system becomes unstable, the transfer function acts as a notch-pass filter passing practically nothing except

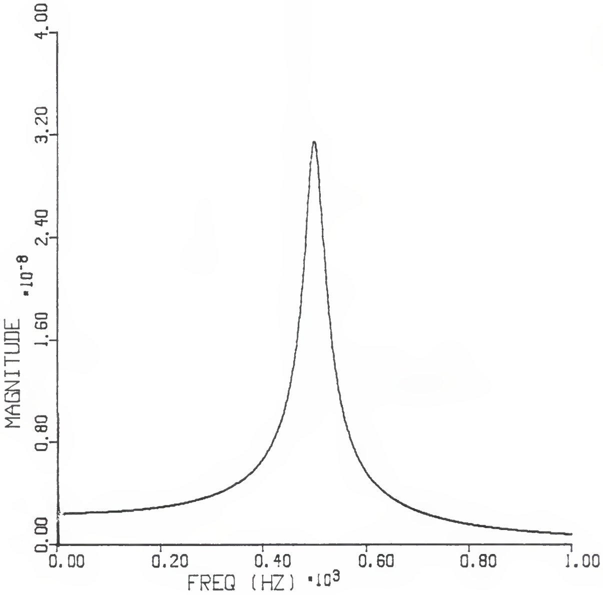


Figure 44 Open-Loop Transfer Function

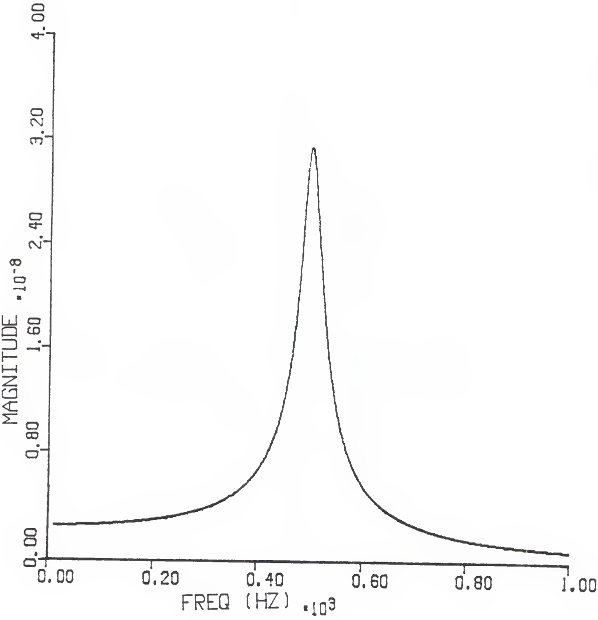


Figure 45 Closed-Loop Transfer Function

the chatter frequency. The reason that the open-loop transfer function is identical to the closed-loop transfer function may be understood with reference to Figures 9 and 10. If the system is stable, then the displacement is driven by the cutting force, which is periodic with respect to the tooth frequency. As a result, the current vibration of the cutter is exactly in phase with the undulations left on the surface by the previous tooth. The chip thickness, which produces the cutting force, is given by the difference between the two. Because the undulations are in phase, the resulting chip thickness is the same as if there were no regeneration of waviness (open-loop). Only when the system becomes unstable and vibrates with a frequency other than the tooth frequency will the open-loop and closed-loop transfer functions differ.

This phenomenon may be very beneficial for the transducer for the automatic spindle speed adjustment algorithm, since once the system is unstable it is important to identify the chatter frequency, and that is practically all that the transfer function of the unstable transfer function will pass. As the tooth frequency approaches the natural frequency and the system becomes stable, then the transfer function of the system becomes the easily-measured open-loop transfer function, and the actual cutting force may be computed with reference to it. Additionally, the transfer function between the end of the tool and the displacement transducer is subjected to far less variation than that of the dynamometer. Further research work is underway in the Machine Tool Laboratory at the University of Florida to investigate the merits of this transducer.

A possible alternative to relying on only one vibration transducer is to use a variety of transducers, each valid under certain conditions, and an artificial intelligence algorithm to select and process a signal or combination of signals to yield the desired information. This is also under development in the Machine Tool Laboratory at the University of Florida.

Equipment Requirements

The requirements for implementation of the algorithm are rather modest, and most of the equipment is readily available. In the following section, both the equipment requirements for commercial implementation and those used in the laboratory verification are mentioned.

As discussed above, the vibration transducer is the most difficult item, and the choice of transducer depends strongly on the application. In the case of the experimental work which follows, a dynamometer mounted between the workpiece and the machine table as shown in Figure 41 was selected as the most convenient system available. The transfer function of the dynamometer in the direction of the milling is shown in Figure 42.

A signal indicative of the spindle speed is required, and is available from the spindle encoder on machines so equipped. In other cases, the signal from the tachometer may be used. In the case of the laboratory work, this signal was provided by a 72-toothed gear attached directly to the spindle. The passage of these teeth under a variable-reluctance pick-up results in a string of pulses which are sampled at the same time as the vibration transducer, providing a signal which is processed into the tooth frequency.

Some sort of data acquisition system is required, and the sampling rate must be at least 2, and preferably 4 times any frequency of interest. In the experimental work, sampling was accomplished using an A/D board attached to an IBM PC-AT, which provided sampling on two channels at a rate of 4000 Hz. These data were stored for later processing on a disk, although the speed could be improved if sufficient RAM were available.

For determining the spectrum of the vibration transducer signal, some implementation of a Fourier Transform is required. For commercial applications, this is available in a hardwired form, which would typically require 62 milliseconds to make a 2048 point complex FFT. In the experimental work this was available as a software subroutine requiring a substantially longer time (several minutes).

In order to make the tooth frequency and largest spectral line comparisons, determine the amplitude of the transducer signal, and to compute new speeds and feed rates in a commercial setting, a microprocessor with appropriate software would be required. The software already exists, and was used in the simulations discussed in Chapter VI. In the laboratory, these comparisons and computations were performed manually, following the same algorithms implemented in the software.

Finally, some connection is necessary for the computer to command new feeds and speeds. The exact commercial implementation depends on access to the existing NC control, but might be by alteration of the program block or by a D/A signal supplied to the feed rate and spindle speed overrides. In the laboratory, these changes were made by manually programming new program blocks.

CHAPTER VIII
EXPERIMENTAL VERIFICATION

The cutting tests described in this section were all performed using a Sundstrand Series 20 Omnimil as illustrated in Figure 46. A 101.6 mm (4 inch) diameter Kennametal ZN3M-0408R2 shell mill was installed in the spindle on an Ingersoll C50-15SM600 extension shell mill holder 152.4 mm (6 inches) long. The cutter had 8 Valenite Q6 SNG632 T00610 silicon nitride inserts, equally spaced around the periphery of the cutter. The workpiece was an ingot of GM 241 gray cast iron, which was attached to an angle plate, which was in turn attached to a dynamometer and the machine table as shown in Figure 41. All cuts were made with the vertical axis (Y axis) of the machine executing the feed motion. The cuts all are 101.6 mm radial immersion and 2.54 mm (0.1 inch) axial immersion. In the optimization process, only the feed rate and spindle speed were varied.

The algorithm is based on the assumption that the dynamics of the machine-tool-workpiece system are unknown, and in this case that was true. Although the transfer function was subsequently measured and the lobing diagram computed as an aid in confirming the procedure, during the

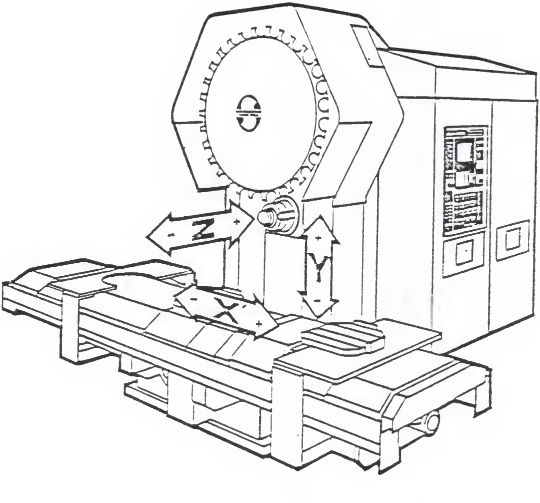


Figure 46 Sundstrand Series 20 Omnimil

actual cutting tests this information was unknown. The tests were performed truly blind.

The initial spindle speed was chosen at random to be 1000 rpm, but it was well within the surface cutting speeds allowed for the inserts. The initial feed rate was chosen to be the recommended minimum [3] of 0.1 mm per tooth (762 mm per minute). The time record of the cutting force signal during the test is shown in Figure 47a, while the corresponding spectrum is presented in Figure 47b (0.5 Hz resolution). With 8 teeth on the cutter, and actual spindle speed (the data given as actual spindle speed are those computed from the encoder signal, not the commanded speeds) of 1003 rpm, the tooth frequency should have been 134 Hz. The peak search algorithm would have detected the clearly dominant peak on the spectrum at 242 Hz. The two frequencies differ considerably, and this is obviously a case of chatter, and arises in a lobe below the optimum spindle speed (it is in lobe N = 1 or greater).

The amplitude of the cutting force signal is seen to be almost 8000 N. In fact, observation of the cut indicated very strong chatter, and it was decided to allow a feed rate even lower than the manufacturer recommended minimum while the optimization process proceeded. This is recommended for future optimizations involving cast iron, titanium, steel, or any other material where the specific power is high, since the actual cutting time at this low feed rate is very

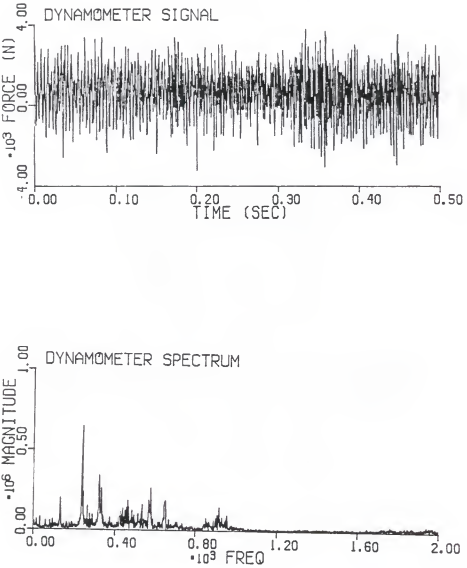


Figure 47 Cutting Test 1, n=1000 rpm, f_t=0.1 mm

short and the risk of excessive tool wear is less threatening than the risk of inserts chipping or breaking because of the chatter.

Based on the frequency of the peak in the first spectrum, a new spindle speed of 1816 rpm was selected (tooth frequency = 242 Hz), and the feed rate was selected as 0.05 mm per tooth (692 mm per minute). The actual spindle speed during the cut was 1816 rpm, which would lead to a tooth frequency of 242 Hz. As shown in Figure 48, however, the again clearly dominant peak in the force spectrum is 326 Hz. From the analysis of the spectrum, this is another clear case of chatter, a fact confirmed by observation of the cut. Even at the lowered feed rate, the amplitude of the force is almost as bad as the first cut. Again the chatter is in a lobe other than N = 0 since the chatter frequency is higher than the tooth frequency.

The second new spindle speed selected was 2446 rpm (corresponding to a 326 Hz tooth frequency), and the feed per tooth was left unchanged (940 mm per minute). The time record and spectrum of this cut are shown in Figure 49. The encoder signal showed that the actual speed was 2410 rpm which would lead to a tooth frequency of 321 Hz, but the peak in the spectrum was 244 Hz. This is chatter in the N = 0 lobe since the chatter frequency is lower than the tooth frequency. In observation, the chatter was not clearly discernible, and the force amplitude was considerably

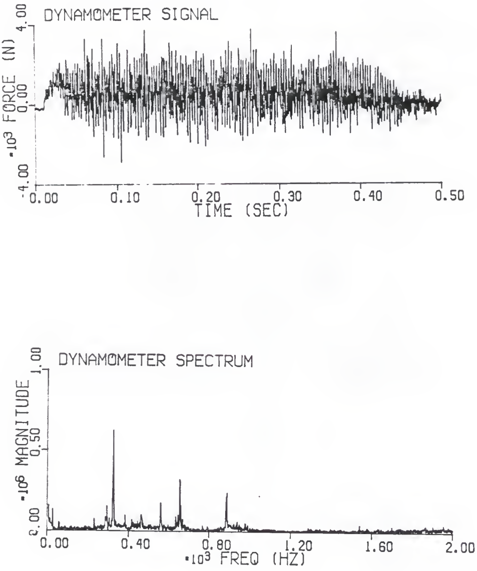
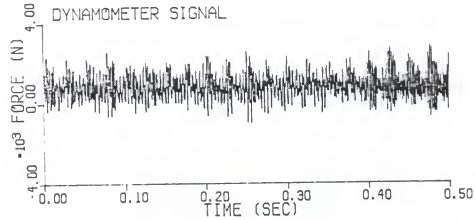


Figure 48 Cutting Test 2, n=1816 rpm, f_t=0.05 mm



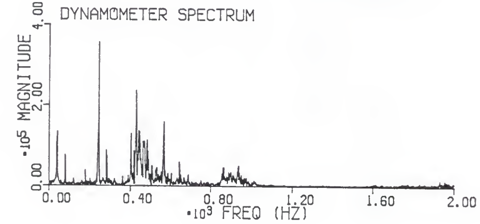


Figure 49 Cutting Test 3, n=2446 rpm, f_t=0.05 mm

improved, but the analysis of the spectrum can confirm the existence of chatter even if the level is very low. A later cut was made with a higher feed rate (0.1 mm per tooth) to confirm that chatter was occurring, and this time chatter was clearly evident.

The third selected cut was at 1831 rpm and feed rate 0.05 mm per tooth. The record is shown in Figure 50. Actual spindle speed of 1830 rpm would produce a tooth frequency of 244 Hz, but the peak in the spectrum is 332 Hz, and the chatter is again occurring in a lobe below the most stable speed. The oscillating convergence is indicative of a case where either the specified cut is extremely unstable or more than one mode is producing chatter.

The fourth selection is for a cut of 2490 rpm with the same feed per tooth, and the records are shown in Figure 51. The encoder signal indicates an actual spindle speed of 2490 rpm, and the tooth frequency would be 332 Hz. In this case, the dominant peak in the spectrum is at 41.5 Hz, which is exactly 8 times less than the tooth frequency and is therefore the runout. Since this is a slotting cut and the cutter has an even number of teeth, in stable machining the runout frequency should dominate the spectrum as discussed in Chapter V. This would be recognized by the algorithm as a stable cut, and observation confirmed that the cut seemed stable. Control in the optimization algorithm would now pass

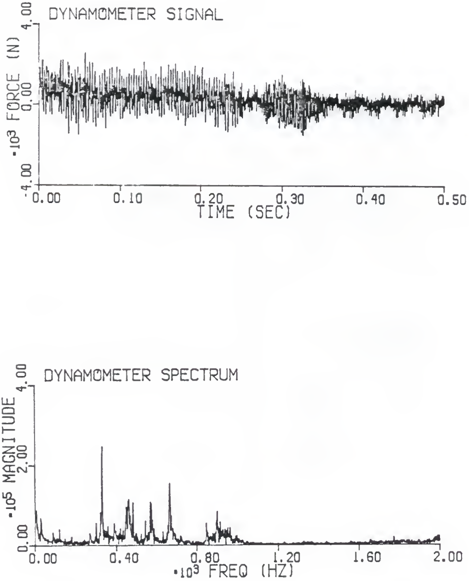


Figure 50 Cutting Test 4, n=1831 rpm, f_t=0.05 mm

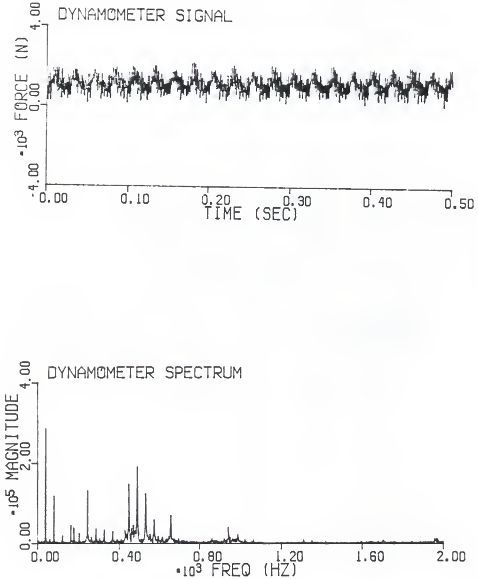


Figure 51 Cutting Test 5, n=2490 rpm, f_t=0.05 mm

to the chip load regulation loop, with no further changes occurring in the spindle speed.

Since no maximum acceptable force level was selected, a cut with the same feed per tooth as the initial cut was taken, and the records are shown in Figure 52. Again the runout dominated the spectrum, and the cut was clearly stable. The amplitude of the cutting force, which arose primarily from the runout, was less than 2000 N. By way of comparison with Figure 47, it may be seen that the amplitude of the force is approximately 4 times less than the initial cut. Additionally, the first cut consumed only about 4.5 kw (6 hp) with a metal removal rate of 0.2 cm^3 of cast iron per minute. The last cut consumed about 11.2 kw (15 hp) with a metal removal rate of almost 0.5 cm^3 per minute.

While the last cut was clearly more stable than the first cut, there are some discrepancies which make direct comparison of the time records somewhat more difficult. The third cut at n = 2446 rpm shows indication of chatter at a frequency lower than the tooth frequency. This is an indication that the stable peak will be found at a lower spindle speed as shown in Figure 24. However, the finally selected speed was 2490 rpm, which is instead a higher speed. During the cutting tests, it was thought that this could be explained as chatter occurring in two different modes. Figure 53, which shows the transfer function of the experimental system measured after the completion of the

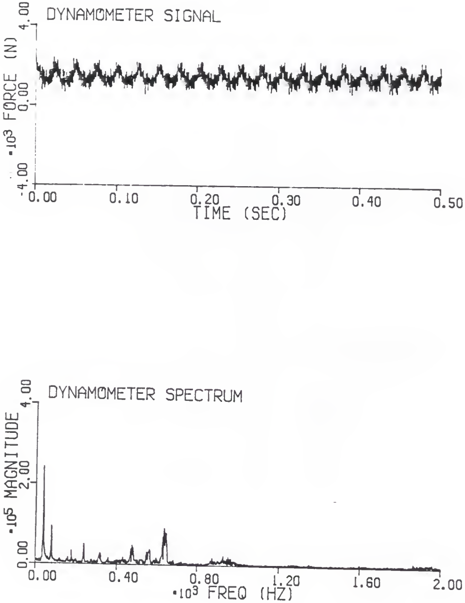


Figure 52 Cutting Test 7, n=2490 rpm, f_t=0.1 mm

"blind" machining tests, shows that this is not the case. It may be seen that the system has only one dominant mode, and that its natural frequency is 345 Hz. However, comparison with Figure 42 reveals an unfortunate coincidence in that the dynamometer transfer function shows a pronounced gap in the same speed range which would cause attenuation of this part of the spectrum of the cutting force. As shown in the stability lobes for the given cut (Figure 54), 2446 rpm was nearly within the stable region, and the magnitude of the developed chatter was low (during the tests, it was not easily distinguished by the observers). The selection of 2490 rpm two cuts later, however is clearly within the stable peak, and no chatter was seen.

This coincidence makes it difficult to compare the amplitudes of the force variation in the time-domain records of the two cuts, so as to demonstrate the degree of improvement which was achieved. However, some evidence is given of the rather strong convergence of the optimization routine. Despite the disappointing frequency characteristics of the dynamometer, the algorithm was able to adjust the spindle speed so as to reach the most stable region within four iterations. The finally selected spindle speed was less than 4 % away from the speed which would have been manually selected if the transfer function had been known a priori, and definitely was a substantial improvement over the first randomly selected cut.

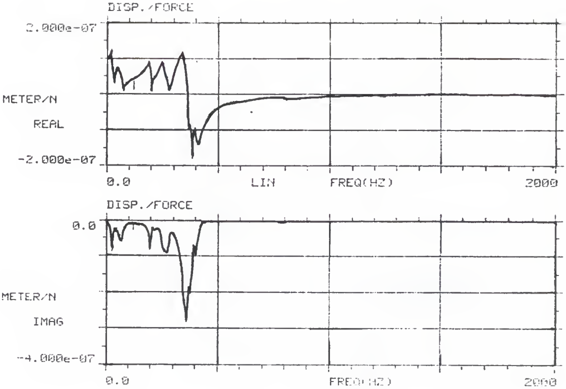


Figure 53 Transfer Function of the Experimental System

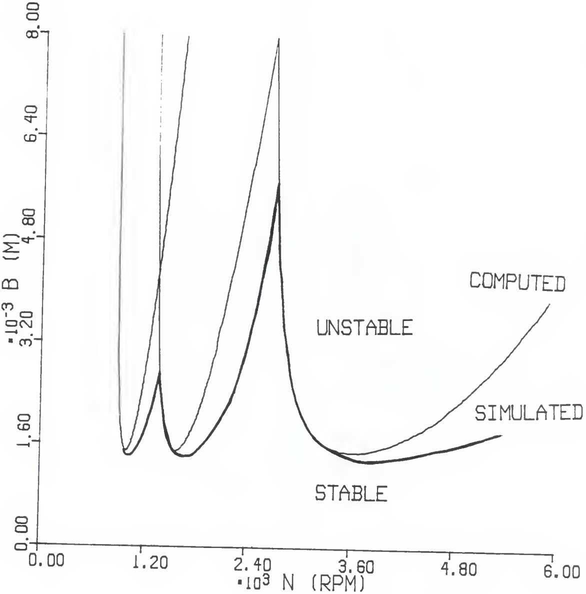


Figure 54 Computed and Simulated Stability Lobes

CHAPTER IX
CONCLUSIONS AND RECOMMENDATIONS

Objective Machining Conditions

For the first time, a method has been developed which shows which spindle speed should be the target speed for an adaptive control algorithm for chatter avoidance in milling. A new type of stability diagram has been developed which through repetitive time-domain simulation shows what force amplitudes, displacement amplitudes, and surface finishes may be expected for a wide variety of cutting conditions. Based on this type of diagram it is easy to see that an adaptive control scheme which would tend to drive the system toward the speed where the tooth frequency equals the natural frequency of the system would in most instances find the attractive stable peak located there.

It was shown that because of the favorable phasing between the displacement of the cutter and the surface left by the preceding teeth within the stable region, the amplitude of the cutting force is practically a constant with respect to spindle speed. It was shown that the surface finish resulting from a stable cut in this region should be very good, although there may be an error in the location of the surface. While the displacement amplitude does not have its minimum at the speed where the tooth frequency equals the natural frequency, it is close, and it is clear that any selection within the stable region is superior to any selection which would lead to chatter.

Practicality of Implementation

An algorithm was shown and tested which would adjust the spindle speed to the stable region rather quickly if that is possible, and would stop the machining if it is not. In experimental work, the algorithm converged quickly to the stable region even though the poor dynamic characteristic of the dynamometer tended to mask the cutting force data.

The hardware required for implementation of the algorithm is commonly available, and all of the software has been shown to work rather well in simulation. It has been shown that the weak link in the whole system is the vibration transducer, which was a table-type dynamometer in the case of the experimental work. All of the transducers considered have some limitation, and the one most appropriate for practical implementation must at present be selected depending on the particular installation. It is possible that a variety of transducers could be included, and that an intelligent control could select the transducer signal or combination of transducer signals most appropriate for the particular conditions being encountered.

Further Work

Developments are at such a stage that a product development is feasible. This is currently envisioned as a corrective patch which could be incorporated into new controller designs or supplied as an "add-on" to existing systems. If inappropriate machining parameters were specified by the programmer, then this system would adjust those parameters which do not cause drastic changes in the part program and would drive the system toward stable machining. The algorithm makes the best of a bad situation by improving the metal removal rate where possible, and at the very least eliminating some of the iterative steps required for proving a new part program.

All of the work presented here assumes that the programmer has very little knowledge of the machine dynamics or the theory of chatter and therefore implies corrective action. Another point of view is possible, which certainly deserves further pursuit. It should be possible to include the machine dynamics and either the actual simulation algorithm or results from the simulation algorithm in to a CAD package. At all times during the programming of a part, the programmer would be aware of the cutting forces, cutter deflections, and surface finishes that would result from the cuts that he is specifying. In this way the CAD system could prevent the mistake in the part program which required the adaptive control algorithm from ever being made. Any required changes in the part program such as redistribution of the cuts or alterations in the feeds and speeds could be made during the original programming when the changes are relatively easy, and the time required for proving part programs could be substantially reduced.

APPENDIX A

OPTIMIZATION SIMULATION PROGRAMS

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                          C
C  MOPT.FOR                                                C
C                                                          C
C  PROGRAM FOR OPTIMIZING SPINDLE SPEED AND FEED RATE      C
C  BASED ON THE CUTTING FORCE SIGNAL                       C
C                                                          C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC


C OPEN THE FILE FOR THE FOURIER TRANSFORM OF THE CUTTING
C FORCE

      OPEN(UNIT=1,FILE='FFT.DAT',STATUS='OLD',ERR=1)
      GOTO 2
     1     OPEN(UNIT=1,FILE='FFT.DAT',STATUS='NEW')

C OPEN THE FILE FOR THE COMPUTED CUTTING FORCE SIGNAL

     2   OPEN(UNIT=2,FILE='FORCES.DAT',STATUS='OLD',ERR=3)
      GOTO 4
     3   OPEN(UNIT=2,FILE='FORCES.DAT',STATUS='NEW')

C OPEN THE FILE OF THE PARAMETERS DESCRIBING THE MILLING
C OPERATION

     4   OPEN(UNIT=3,FILE='MPARAM.DAT',STATUS='OLD')

C OPEN THE OUTPUT FILE FOR THE CHOSEN FEEDS, SPEEDS, AND PTP
C FORCES

      OPEN(UNIT=4,FILE='OPT.DAT',STATUS='NEW')
      READ(3,*)PHIS,PHIE,TETH,I,XKS,NMAX
      REWIND 3
      WRITE(*,*)'INPUT MINIMUM FEED PER TOOTH (MM)'
      READ(*,*)FTMIN
      FTMIN=FTMIN/1000.
      WRITE(*,*)'INPUT MAXIMUM FEED PER TOOTH (MM)'
      READ(*,*)FTMAX
      FTMAX=FTMAX/1000.
      FTFACT=(FTMAX-FTMIN)/10.
      WRITE(*,*)
      WRITE(*,*)
      CRFRQ=150.
      WRITE(*,*)'ENTER INITIAL FEED PER TOOTH IN MM'
      READ(*,*)FT
      FT=FT/1000.
      WRITE(*,*)'ENTER MAXIMUM SPINDLE SPEED IN RPM'
      READ(*,*)SSMAX
      WRITE(*,*)'ENTER INITIAL SPINDLE SPEED IN RPM'
      READ(*,*)SS
      WRITE(*,*)'ENTER AXIAL DEPTH OF CUT B IN MM'
      READ(*,*)B
      B=B/1000.
      WRITE(*,*)'ENTER MAXIMUM PERMITTED PTP'
      READ(*,*)PTPMAX
      WRITE(*,*)
      WRITE(*,*)

C INITIALIZE FLAG SIGNALING PTP FORCE TOO HIGH

      IFFT=0

C INITIALIZE FLAG SIGNALING IF FEED HAS BEEN REDUCED

      PFLAG=0.

C INITIALIZE ITERATION COUNTER

      ITRY=1

 10   CONTINUE

C CALL TO THE MILLING SIMULATION SUBROUTINE

      CALL MILXYT(SS,B,FT,3,0,0,2,0,0,0)

C CALL SUBROUTINE TO CHECK IF THE PTP FORCE IS ACCEPTABLE
      CALL PTP(PTPACT,CRFRQ,2)
      IF(PTPACT.GT.PTPMAX)THEN
      IFFT=1
      ELSE
      IFFT=0
      ENDIF


      WRITE(*,*)'SPINDLE SPEED =',SS
      WRITE(*,*)'AXIAL DEPTH OF CUT =',B*1000.
      WRITE(*,*)'FEED PER TOOTH =',FT*1000.
      WRITE(*,*)'PTP PERMITTED =',PTPMAX
      WRITE(*,*)'PTP ACTUAL =',PTPACT
      WRITE(*,*)'ITERATION =',ITRY
      WRITE(4,*)ITRY,SS,PTPACT,FT,B
      WRITE(*,*)
      WRITE(*,*)

C INCREMENT ITERATION COUNTER

      ITRY=ITRY+1

C BRANCH AROUND OPTION TO STOP IF FEED WAS DROPPED

      IF(PFLAG.EQ.1.)GOTO 11
```

```
C IF THE PTP FORCE LEVEL IS TOO HIGH,

      IF(IFFT.EQ.1)THEN

C IMMEDIATELY DROP FEED RATE TO MINIMUM ALLOWED

      FT=FTMIN

C SET FEED RATE DROP FLAG

      PFLAG=1.

   11     CONTINUE

C CALL SUBROUTINE FOR FOURIER TRANSFORM OF CUTTING FORCE

      IF(PTPACT.LT.(FTMIN/FTMAX*2*PTPMAX))THEN
      GOTO 20
      ENDIF

      CALL FTRANS(2,1)


C KEEP PREVIOUS SPINDLE SPEED FOR COMPARISON

      SSO=SS

C CALL SUBROUTINE TO LOCATE LARGEST PEAK ON SPECTRUM OF
C CUTTING FORCE AND RECOMMEND NEW SPINDLE SPEED

      CALL PSSS(1,FH,XH,TETH,CRFRQ,NMAX)

      DO 21 ISS=1,5
      SS=FH/FLOAT(ISS)*60./TETH
      IF(SS.LT.SSMAX) GOTO 22
   21     CONTINUE
   22     CONTINUE

      WRITE(*,*)'NEW SS=',SS

C CHECK IF NEW RECOMMENDED SPEED IS SUFFICIENTLY CLOSE TO
C OLD SPEED

      IF((SS.GT.(SSO-.02*SSO)).AND.(SS.LT.(SSO+.02*SSO)))THEN

C IF SO, EXIT LOOP
      GOTO 20
C CHECK IF NEW RECOMMENDED SPEED IS CAUSED BY RUNOUT
      ELSE
      IF(((SS*TETH).GT.(SSO-.02*SSO)).AND.((SS*TETH).LT.
     $(SSO+.02*SSO))) GOTO 20
```

```
      ENDIF

C ELSE RETURN TO SIMULATION WITH NEW SPEED

      GOTO 10
      ENDIF



   20     CONTINUE
C     ITRY=ITRY-1


C IF FORCE LEVEL IS STILL TOO HIGH USING BEST SPEED AND
C MINIMUM FEEDRATE, OUTPUT ERROR MESSAGE AND STOP

      IF(IFFT.EQ.1)THEN
      WRITE(*,*)'PTP FORCE USING BEST SPEED AND MINIMUM
     $ FEEDRATE =',PTPACT
      WRITE(*,*)'PTP FORCE SPECIFIED =',PTPMAX
      WRITE(*,*)'PROGRAM MUST BE CHANGED TO ACHIEVE THE
     $ DESIRED FORCE LEVEL'
      STOP
      ENDIF


C ONCE BEST SPEED IS ACHIEVED, BEGIN LOOP TO RAISE FEEDRATE

      DO 31 II=1,11

C     RAISE FEEDRATE

      FT=FT+FTFACT

C CALL TO SIMULATION SUBROUTINE

      CALL MILXYT(SS,B,FT,3,0,0,2,0,0,0)

C SAVE OLD FORCE LEVEL IN CASE NEW FEED IS TOO HIGH

      PTPAO=PTPACT

C CALL SUBROUTINE TO CHECK NEW FORCE LEVEL
      CALL PTP(PTPACT,CRFRQ,2)
      IF(PTPACT.GT.PTPMAX)THEN
      IFFT=1
      ELSE
      IFFT=0
      ENDIF

      WRITE(*,*)'SPINDLE SPEED =',SS
      WRITE(*,*)'AXIAL DEPTH OF CUT =',B*1000.
      WRITE(*,*)'FEED PER TOOTH =',FT*1000.
      WRITE(*,*)'PTP PERMITTED =',PTPMAX
      WRITE(*,*)'PTP ACTUAL =',PTPACT
      WRITE(*,*)'ITERATION =',ITRY
      WRITE(4,*)ITRY,SS,PTPACT,FT,B
      WRITE(*,*)
      WRITE(*,*)
      ITRY=ITRY+1

C IF FORCE LEVEL LIMIT IS EXCEEDED BY RAISING FEED, OR IF
C MAX FEED EXCEEDED, USE PREVIOUS FEED AND STOP

      IF((IFFT.EQ.1).OR.(FT.GT.1.001*FTMAX)) THEN
      WRITE(*,*)
      WRITE(*,*)
      WRITE(*,*)'FINAL CUTTING CONDITIONS'
      WRITE(*,*)
      WRITE(*,*)'SPINDLE SPEED =',SS,'(RPM)'
      WRITE(*,*)'AXIAL DEPTH OF CUT =',B*1000.,'(MM)'
      WRITE(*,*)'FEED PER TOOTH =',(FT-FTFACT)*1000.,'(MM)'
      WRITE(*,*)'PTP PERMITTED =',PTPMAX,'(N)'
      WRITE(*,*)'PTP ACTUAL =',PTPAO,'(N)'
      WRITE(*,*)'ITERATIONS =',ITRY-2
      WRITE(4,*)ITRY-2,SS,PTPAO,FT-FTFACT,B
      STOP
      ENDIF

31    CONTINUE
      STOP
      END
```

APPENDIX B

MILLING SIMULATION AND OTHER UTILITY PROGRAMS

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                          C
C         SUBROUTINE FOR CALCULATING PTP                   C
C                                                          C
C  INPUTS                                                  C
C   CRFRQ - DESIRED CORNER FREQUENCY FOR THE 2nd ORDER     C
C           BUTTERWORTH  HIGH-PASS FILTER TO BE APPLIED    C
C           TO THE DATA                                    C
C    NF   - UNIT NUMBER OF THE OPEN FILE WHERE THE DATA    C
C           ARE LOCATED (TWO FREE-FORMAT COLUMNS, TIME     C
C           IN THE FIRST COLUMN)                           C
C                                                          C
C   OUTPUTS                                                C
C   PTPACT - PEAK TO PEAK AMPLITUDE OF THE DATA            C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

      SUBROUTINE PTP(PTPACT,CRFRQ,NF)
      REWIND NF
      PI=ACOS(-1.)
      FMAX=1.E-9
      FMIN=1.E9
      DO 5 I=1,10000
          READ(NF,*,END=6)T,D
       IF(I.EQ.1)T1=T
       IF(I.EQ.2)T2=T
     5     CONTINUE
     6     CONTINUE
      REWIND NF
      DT=T2-T1
      VMAX=I-1

C       FILTER INITIALIZATION

      CR=TAN(2.*PI*CRFRQ*DT/2.)
      C1=1.-1.4142*CR+CR**2
      C2=2.*CR**2-2
      C3=1.+1.4142*CR+CR**2
      D1H=0.
      D2H=0.
      DF1H=0.
      DF2H=0.

      DO 10 I=1,VMAX
       READ(NF,*,END=11)T,D

C      FILTER
       DF0=(D2H-2.*D1H+D-C1*DF2H-C2*DF1H)/C3
       D2H=D1H
       D1H=D
       DF2H=DF1H
       DF1H=DF0
      IF (I.GT.VMAX-VMAX/2.)THEN
       IF (ABS(DF0).GT.FMAX)THEN
        FMAX=ABS(DF0)
        SMAX=1.
        IF(DF0.LT.0)SMAX=-1.
       ENDIF
       IF (ABS(DF0).LT.FMIN)THEN
        FMIN=ABS(DF0)
        SMIN=1.
        IF(DF0.LT.0)SMIN=-1.
          ENDIF
      ENDIF
10        CONTINUE
11        CONTINUE

     PTPACT=ABS(FMAX-SMAX*SMIN*FMIN)

     REWIND NF
     RETURN
     END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                          C
C       SUBROUTINE FOR MILLING SIMULATION                  C
C                                                          C
C    INPUTS                                                C
C         SS  - SPINDLE SPEED (RPM)                        C
C          B   - AXIAL DEPTH OF CUT (M)                    C
C          NF  - UNIT NUMBER OF OPEN FILE CONTAINING       C
C                SIMULATION PARAMETERS IN THE FORMAT:      C
C                                                          C
C                    PHIS PHIE TETH I KS NMAX              C
C                    NX                                    C
C                    KX1 ZX1 MX1                           C
C                    KX2 ZX2 MX2                           C
C                    ...                                   C
C                    NY                                    C
C                    KY1 ZY1 MY1                           C
C                    KY2 ZY2 MY2                           C
C                    ...                                   C
C                                                          C
C             WHERE:                                       C
C               PHIS - THE ANGLE OF ENTRY INTO THE CUT     C
C               PHIE - THE ANGLE OF EXIT FROM THE CUT      C
C               TETH - THE NUMBER OF TEETH ON THE CUTTER   C
C                 I  - THE NUMBER OF SIMULATION STEPS      C
C                       BETWEEN SUBSEQUENT TEETH           C
C                 KS - SPECIFIC POWER (N/M*2)              C
C               NMAX - MAXIMUM NUMBER OF SIMULATION STEPS  C
C                                                          C
C            NX - NUMBER OF X-DIRECTION MODES (UP TO 10)   C
C           KXn - AN X-DIRECTION MODAL STIFFNESS  (N/M)    C
C           ZXn - AN X-DIRECTION MODAL DAMPING RATIO       C
C           MXn - AN X-DIRECTION MODAL MASS  (KG)          C
C            NY - NUMBER OF Y-DIRECTION MODES (UP TO 10)   C
C           KYn - AN Y-DIRECTION MODAL STIFFNESS  (N/M)    C
C           ZYn - AN Y-DIRECTION MODAL DAMPING RATIO       C
C           MYn - AN Y-DIRECTION MODAL MASS  (KG)          C
C                                                          C
C           NOX - UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME C
C                   AND X DISPLACEMENT                     C
C           NOY - UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME C
C                   AND Y DISPLACEMENT                     C
C           NOFX- UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME C
C                   AND X FORCE                            C
C           NOFY- UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME C
C                   AND Y FORCE                            C
C           NOSX- UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME C
C                   AND X SURFACE PROFILE                  C
C           NOSY- UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME C
C                   AND Y SURFACE PROFILE                  C
C                                                          C
C      *NOTE: ENTERING 0 FOR A PARTICULAR UNIT NUMBER      C
```

```
C              WILL PREVENT THAT FILE FROM BEING WRITTEN    C
C                                                            C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC


      SUBROUTINE MILXYT(SS,B,FT,NF,NOX,NOY,NOFX,NOFY,NOSX,NOSY)
        DIMENSION Z(2048),XX(10,6),YY(10,6)
        DO IZ=1,2048
        Z(IZ)=0.
        END DO
        PI=ACOS(-1.)
        TR=PI/180.

        READ(NF,*)PHIS,PHIE,TETH,I,XKS,NMAX
        PHIS=PHIS*TR
        PHIE=PHIE*TR
        PP=2.*PI/TETH
        DPHI=PP/FLOAT(I)
        DT=60./(FLOAT(I)*TETH*SS)
        DELT=20.*TR

        READ(NF,*)NX
        DO 10 IX=1,NX
         XX(IX,1)=0.
         XX(IX,2)=0.
         XX(IX,3)=0.
         READ(NF,*)(XX(IX,JX),JX=4,6)
         XX(IX,5)=2.*XX(IX,5)*SQRT(XX(IX,4)*XX(IX,6))
      10   CONTINUE

        READ(NF,*)NY
        DO 20 IY=1,NY
         YY(IY,1)=0.
         YY(IY,2)=0.
         YY(IY,3)=0.
         READ(NF,*)(YY(IY,JY),JY=4,6)
         YY(IY,5)=2.*YY(IY,5)*SQRT(YY(IY,4)*YY(IY,6))
      20   CONTINUE
        REWIND NF

        PHI=PHIS
        NN=1
        X=0.
        Y=0.
        DO 100 N=1,NMAX
         NE=INT(ABS((PHI-PHIS)/PP))
         IF((PHI-PHIE).LT.0)NE=NE+1
         XF=0.
         YF=0.
         IF (NE.EQ.0) THEN
          F=0.
```

```
       GO TO 200
      ENDIF

      DO 200 K=1,NE
       PHIL=PHI-(FLOAT(K-1)*PP)
       IF(NOSX.NE.0)THEN
        IF(PHIL.LT.DPHI)WRITE(NOSX,*)N*DPHI/TR/6./SS,X
       ENDIF

       IF(NOSY.NE.0)THEN
        IF(PHIL.LT.DPHI)WRITE(NOSY,*)N*DPHI/TR/6./SS,Y
       ENDIF

       ZZ=X*SIN(PHIL)+Y*COS(PHIL)
       IF(N.LT.(I+1))THEN
        ZZ=FT*SIN(PHIL)
        ZBACK=0.
       ELSE
        ZBACK=Z(NN-((K-1)*I))-FT*SIN(PHIL)
       ENDIF

       F=XKS*B*(ZZ-ZBACK)
       IF(F.LT.0.) F=0.

       PHIF=PHIL-DELT
       XF=XF-F*COS(PHIF)
       YF=YF+F*SIN(PHIF)
       Z(NN-((K-1)*I))=AMAX1(ZZ,ZBACK)
200      CONTINUE

      X=0.
      DO 30 IX=1,NX
       XX(IX,3)=(XF-XX(IX,5)*XX(IX,2)-XX(IX,4)*XX(IX,1))
     $/XX(IX,6)
       XX(IX,2)=XX(IX,2)+XX(IX,3)*DT
       XX(IX,1)=XX(IX,1)+XX(IX,2)*DT
       X=X+XX(IX,1)
 30        CONTINUE

         Y=0.
      DO 40 IY=1,NY
       YY(IY,3)=(YF-YY(IY,5)*YY(IY,2)-YY(IY,4)*YY(IY,1))
     $/YY(IY,6)
       YY(IY,2)=YY(IY,2)+YY(IY,3)*DT
       YY(IY,1)=YY(IY,1)+YY(IY,2)*DT
       Y=Y+YY(IY,1)
 40        CONTINUE

      IF(NOX.NE.0)WRITE(NOX,*)N*DPHI/TR/6./SS,X
      IF(NOY.NE.0)WRITE(NOY,*)N*DPHI/TR/6./SS,Y
      IF(NOFX.NE.0)WRITE(NOFX,*)N*DPHI/TR/6./SS,XF
      IF(NOFY.NE.0)WRITE(NOFY,*)N*DPHI/TR/6./SS,YF
```

```
    NN=NN+1
    PHI=PHI+DPHI
    RESET=AMAX1((ABS(PHIS-PP)),ABS(PHIE-PHIS))
    DOWHILE(ABS(PHI-PHIS).GT.RESET)
    PHI=PHI-PP
    NN=NN-I
    ENDDO
100   CONTINUE
   PHIS=PHIS/TR
   PHIE=PHIE/TR
   IF(NOX.NE.0)REWIND NOX
   IF(NOY.NE.0)REWIND NOY
   IF(NOFX.NE.0)REWIND NOFX
   IF(NOFY.NE.0)REWIND NOFY
   IF(NOSX.NE.0)REWIND NOSX
   IF(NOSY.NE.0)REWIND NOSY
   RETURN
      END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                           C
C     SUBROUTINE FOR CALCULATING PTP OF SURFACE FINISH,    C
C     FORCE, OR DISPLACEMENT IN A MILLING OPERATION FOR    C
C     VARIOUS AXIAL DEPTHS OF CUT AND SPINDLE SPEEDS WITH   C
C     DATA FILE STORAGE FOR SUBSEQUENT ANALYSIS.            C
C                                                           C
C INPUTS                                                    C
C SSIN  - LOWEST SPINDLE SPEED IN RANGE OF INTEREST (RPM)   C
C SSFIN - HIGHEST SPINDLE SPEED IN RANGE OF INTEREST (RPM)  C
C SSINC - SPINDLE SPEED INCREMENT (RPM)                     C
C   BIN - LOWEST AXIAL DEPTH OF CUT IN RANGE OF             C
C         INTEREST (M)                                      C
C  BFIN - HIGHEST AXIAL DEPTH OF CUT IN RANGE OF            C
C         INTEREST (M)                                      C
C  BINC - AXIAL DEPTH OF CUT INCREMENT (M)                  C
C    FT - FEED PER TOOTH (M)                                C
C CRFRQ - CORNER FREQUENCY FOR 2nd ORDER BUTTERWORTH        C
C         FILTER APPLIED TO ELIMINATE DC COMPONENT FOR      C
C         PTP COMPUTATION                                   C
C    NF - UNIT NUMBER OF OPEN FILE CONTAINING MILLING       C
C         SIMULATION PARAMETERS                             C
C   NOX - UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME AND     C
C         X DISPLACEMENT                                    C
C   NOY - UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME AND     C
C         Y DISPLACEMENT                                    C
C  NOFX - UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME AND     C
C         X FORCE                                           C
C  NOFY - UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME AND     C
C         Y FORCE                                           C
C  NOSX - UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME AND     C
C         X SURFACE PROFILE                                 C
C  NOSY - UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME AND     C
C         Y SURFACE PROFILE                                 C
C  NOSX - UNIT NUMBER OF OPEN OUTPUT FILE FOR TIME AND     C
C         X SURFACE PROFILE                                 C
C NMATX - UNIT NUMBER OF OPEN OUTPUT FILE FOR PTP’s OF      C
C         X DISPLACEMENT                                    C
C NMATY - UNIT NUMBER OF OPEN OUTPUT FILE FOR PTP’s OF      C
C         Y DISPLACEMENT                                    C
C NMATFX- UNIT NUMBER OF OPEN OUTPUT FILE FOR PTP’s OF      C
C         X FORCE                                           C
C NMATFY- UNIT NUMBER OF OPEN OUTPUT FILE FOR PTP’s OF      C
C         Y DISPLACEMENT                                    C
C NMATSX- UNIT NUMBER OF OPEN OUTPUT FILE FOR PTP’s OF      C
C         X SURFACE PROFILE                                 C
C NMATSY- UNIT NUMBER OF OPEN OUTPUT FILE FOR PTP’s OF      C
C         Y SURFACE PROFILE                                 C
C                                                           C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
      SUBROUTINE PTPMAT(SSIN,SSFIN,SSINC,BIN,BFIN,
      $ BINC,FT,CRFRQ NF,NOX,NOY,NOFX,NOFY,NOSX,NOSY,
      $ NMATX,NMATY,NMATFX,NMATFY,NMATSX,NMATSY)
      DIMENSION PTPA(6,100)

      ISM=INT((SSFIN-SSIN)/SSINC)
      IBM=INT((BFIN-BIN)/BINC)

      B=BIN
      DO 10 IB=1,IBM
       SS=SSIN
       DO 20 IS=1,ISM
        CALL MILXYT(SS,B,FT,NF,NOX,NOY,NOFX,NOFY,NOSX,NOSY)
        IF(NOX.NE.0)THEN
         CALL PTP(PTPACT,CRFRQ,NOX)
         PTPA(1,IS)=PTPACT
        ENDIF
        IF(NOY.NE.0)THEN
         CALL PTP(PTPACT,CRFRQ,NOY)
         PTPA(2,IS)=PTPACT
        ENDIF
        IF(NOFX.NE.0)THEN
         CALL PTP(PTPACT,CRFRQ,NOFX)
         PTPA(3,IS)=PTPACT
        ENDIF
        IF(NOFY.NE.0)THEN
         CALL PTP(PTPACT,CRFRQ,NOFY)
         PTPA(4,IS)=PTPACT
        ENDIF
        IF(NOSX.NE.0)THEN
         CALL PTP(PTPACT,CRFRQ,NOSX)
         PTPA(5,IS)=PTPACT
        ENDIF
        IF(NOSY.NE.0)THEN
         CALL PTP(PTPACT,CRFRQ,NOSY)
         PTPA(6,IS)=PTPACT
        ENDIF

        SS=SS+SSINC
    20    CONTINUE

       IF(NOX.NE.0)WRITE(NMATX,*)(PTPA(1,IS),IS=1,ISM)
       IF(NOY.NE.0)WRITE(NMATY,*)(PTPA(2,IS),IS=1,ISM)
       IF(NOFX.NE.0)WRITE(NMATFX,*)(PTPA(3,IS),IS=1,ISM)
       IF(NOFY.NE.0)WRITE(NMATFY,*)(PTPA(4,IS),IS=1,ISM)
       IF(NOSX.NE.0)WRITE(NMATSX,*)(PTPA(5,IS),IS=1,ISM)
       IF(NOSY.NE.0)WRITE(NMATSY,*)(PTPA(6,IS),IS=1,ISM)

       B=B+BINC
    10     CONTINUE
      IF(NOX.NE.0)REWIND NOX
      IF(NOY.NE.0)REWIND NOY
      IF(NOFX.NE.0)REWIND NOFX
      IF(NOFY.NE.0)REWIND NOFY
      IF(NOSX.NE.0)REWIND NOSX
      IF(NOSY.NE.0)REWIND NOSY
      IF(NMATX.NE.0)REWIND NMATX
      IF(NMATY.NE.0)REWIND NMATY
      IF(NMATFX.NE.0)REWIND NMATFX
      IF(NMATFY.NE.0)REWIND NMATFY
      IF(NMATSX.NE.0)REWIND NMATSX
      IF(NMATSY.NE.0)REWIND NMATSY
      RETURN
      END
```

```
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
C                                                          C
C     FAST FOURIER TRANSFORM PROGRAM                       C
C                                                          C
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc

     SUBROUTINE FTRANS(NFI,NFO)
     DIMENSION X(10000),XT(10000),T(10000)
     COMPLEX XC(10000)

C DATA INPUT AND PREPARATION

     DO 10 I=1,10000
     READ(NFI,*,END=11)T(I),XT(I)
   10      CONTINUE
   11    CONTINUE
     REWIND NFI
     I=I-1
     DT=T(2)-T(1)
     FRQRNG=1./DT/2.
     IF(I.LT.1024)THEN
     WRITE(*,*)'TOO FEW DATA POINTS'
     WRITE(*,*)'THERE MUST BE AT LEAST 1024 POINTS'
     STOP
     ENDIF
     NFRAMS=INT(I/1024)
     M=INT(ALOG(FLOAT(I))/ALOG(2.))
     L=INT(2**M)
     NEGL=I-L
     NL=I-NEGL
     NH=I
     RES=FRQRNG/L*2
     IF(NEGL.NE.0)THEN
     NL=0
     NH=NEGL
     END IF
     LL=1
     DO 16 K=1,L
     IF ((K.GT.NL).AND.(K.LT.NH)) GO TO 16
     XC(LL)=CMPLX(XT(LL),0.)
     LL=LL+1
   16      CONTINUE

C CALL TO FOURIER TRANSFORM SUBROUTINE

     CALL FFT(XC,M)
     F=0.
     DO 17 K=1,LL/2
     XMAG=CABS(XC(K))
     WRITE(NFO,*)F,XMAG
     F=F+RES
   17      CONTINUE
```

```
     REWIND NFO
     END

C FFT SUBROUTINE USING OPPENHEIM

        SUBROUTINE FFT(X,M)
        COMPLEX X(1024),U,W,T
        N=2**M
        PI=ACOS(-1.)
        DO 20 L=1,M
        LE=2**(M+1-L)
        LE1=LE/2
        U=(1.0,0.0)
        W=CMPLX(COS(PI/FLOAT(LE1)),-SIN(PI/FLOAT(LE1)))
        DO 20 J=1,LE1
        DO 10 I=J,N,LE
        IP=I+LE1
        T=X(I)+X(IP)
        X(IP)=(X(I)-X(IP))*U
        X(I)=T
   10   CONTINUE
   20   U=U*W
        NV2=N/2
        NM1=N-1
        J=1
        DO 30 I=1,NM1
        IF(I.GE.J)GO TO 25
        T=X(J)
        X(J)=X(I)
        X(I)=T
   25   K=NV2
   26   IF(K.GE.J)GO TO 30
        J=J-K
        K=K/2
        GO TO 26
   30   J=J+K
        RETURN
        END
```

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                           C
C    PEAK SEARCH SUBROUTINE                                 C
C                                                           C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

     SUBROUTINE PSSS(NF,FH,XH,TETH,FC,NMAX)
     XH=0.
     FH=0.
     DO 10 I=1,NMAX/2
     READ(NF,*,END=11)F,XM
     IF (F.EQ.0)GOTO 10

C HIGH PASS FILTER

     XM=XM/SQRT(1.+(FC/F)**2)
     IF(XM.GT.XH)THEN
     XH=XM
     FH=F
     ENDIF
   10     CONTINUE
   11     CONTINUE
     REWIND NF
     RETURN
     END
```

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BIOGRAPHICAL SKETCH

The author was born on January 26, 1961, in Minot, North Dakota. He spent the majority of his life in Cookeville, Tennessee, and received his B.S. from Tennessee Technological University while there. He completed all of his graduate studies at the University of Florida in Gainesville, where he currently resides with his wife, Jan. He plans to pursue an academic career after graduation, following in the footsteps of his father.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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